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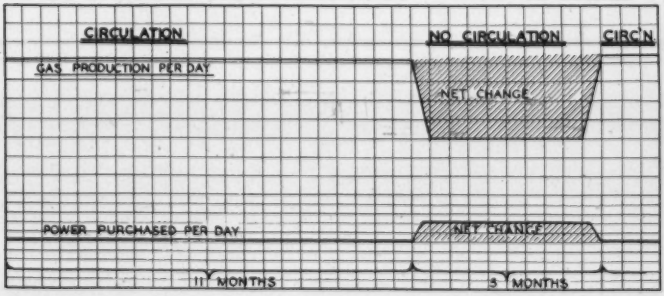


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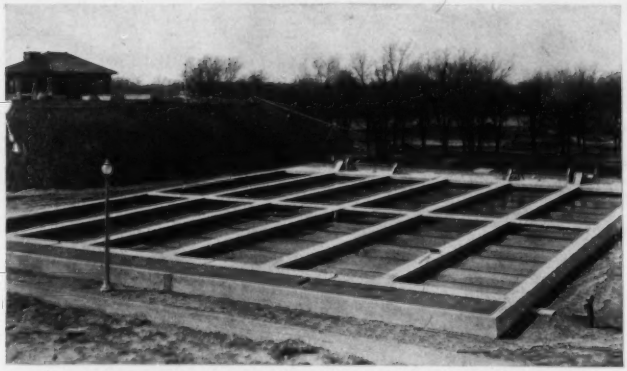

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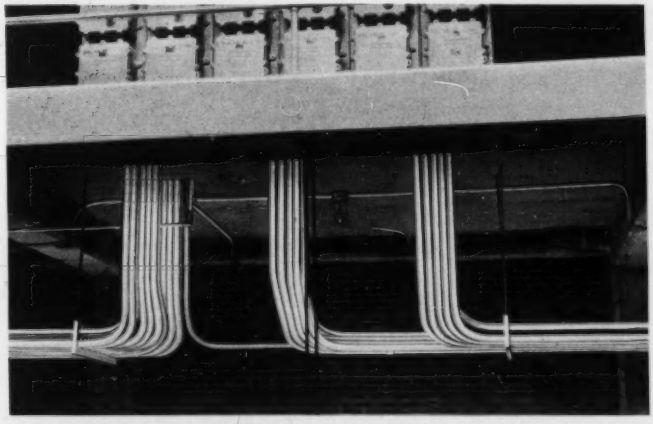

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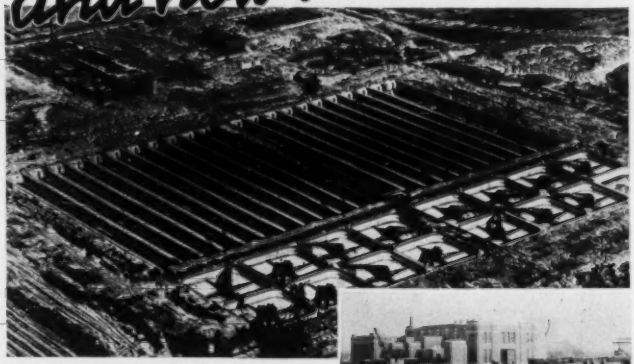

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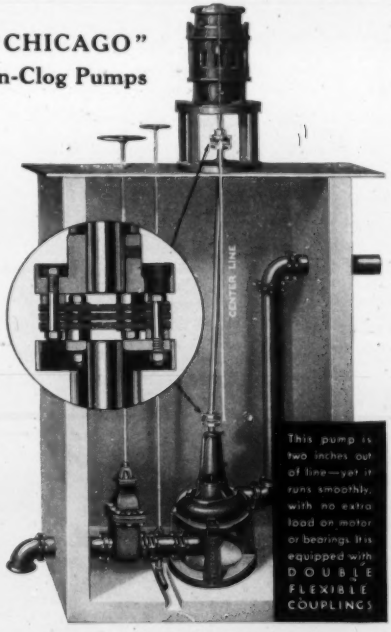
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Research in Sewage Chemistry, Sewage Treatment and Stream Pollution. A Critical Review of the Literature of 1934. By Wellington Donaldson, Linn H. Enslow, L. M. Fisher, Samuel A. Greeley, W. S. Mahlie, Willem Rudolfs and Earle B. Phelps, *Chairman* ..... 149

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# Sewage Research

## RESEARCH IN SEWAGE CHEMISTRY, SEWAGE TREATMENT AND STREAM POLLUTION

### A CRITICAL REVIEW OF THE LITERATURE OF 1934

By Wellington Donaldson, Linn H. Enslow, L. M. Fisher, Samuel A. Greeley, W. S. Mahlie, Willem Rudolfs and Easle B. Phelps, *Chairman*

*Committee on Research, Federation of Sewage Works Associations*

### Chemistry and Biology

Results of interesting and valuable research have been reported in 1934 concerning the nature and amount of dispersed matter in sewage, particularly the extremely fine material and colloidal substances. Experiments conducted at the University College, London [1] indicate that such matter carries a small negative charge at pH 6.0 and a slightly positive charge at pH 2.0. More recent studies [2] have shown that the quantity of dispersate that can be removed by centrifuging or by ultrafiltration is increased by passing gas bubbles (air, oxygen, hydrogen, nitrogen) through sewage. Even particles so small as to pass an ultrafilter can be coagulated or flocculated by the action of the bubbles of gas. Greater removal of organic carbon and total nitrogen resulted from the action of oxygen and air than from that of bubbles of hydrogen and nitrogen. It seems likely, therefore, that both physical and chemical changes occurred. With regard to the chemical composition of the dispersed matter, the solids dehydrated by successive washings with alcohol and ether were largely soluble in ammoniacal copper sulphate, indicating a large proportion of cellulose.

The composition and characteristics of sewage solids have been further investigated by Knechtges, Peterson and Strong [4] who found, on fractionation of petroleum ether and chloroform extracts, that free fatty acids constituted the largest fraction, followed by soaps, hydrolyzable fat and unsaponifiable matter.

Studies are reported from Rothamsted [2] on the biological oxidation of fats and soaps, important constituents of domestic sewage and of certain industrial wastes. The proportions of these constituents in solution and as suspended solids are dependent not only on the quantities and composition of the fats and soaps discharged with the wastes, but also on other substances in solution. Three laboratory filters, made of glass vessels filled with small glass tubes as filter media, were used for test-

ing and the purification was measured by B.O.D. reduction. One filter received (*a*) 250 p.p.m. sodium stearate, 15 p.p.m. $P_2O_5$ as potassium phosphate and 30 p.p.m. N as ammonium bicarbonate placed in distilled water; (*b*) 250 p.p.m. sodium stearate added to sewage previously treated to remove the Ca and Mg to avoid precipitation of the stearate; (*c*) sewage to which 15 p.p.m. $P_2O_5$ as potassium phosphate had been added. The rate of application was 100 gallons per day per cubic yard of filtering medium. The filters were operated for six months. The purification effected by filter A, with stearate alone, fluctuated widely from day to day, varying from 18 to 97 per cent. Quantities of white solid matter were deposited in the upper section of the filter. The experiments indicated that soap in sewage in concentrations as high as 250 p.p.m could be readily oxidized by the filter, but that the process was not satisfactory for solutions of soap alone. The presence of soap in the sewage increased the tendency to clog.

Hydrogen sulphide production in sewage is of importance because of odor production and sewer disintegration. It has been assumed that hydrogen sulphide production is affected not only by the organic matter of the sewage but also by the materials in solution. Baumgartner,[5] experimenting with stale sewage solids, found that seeding with hydrogen sulphide-producing organisms and also higher temperatures, increased the production of the gas. Sodium bicarbonate and dextrose did not affect the rate of production. Ferric chloride added in small quantities reduced $H_2S$ by precipitation of the volatile sulphides present in the sewage.

*Sludge Digestion.*—The number of papers dealing with sludge digestion appearing during recent years has somewhat abated. Several papers have been published by English investigators, of which those of Edmondson and Ardern and Lockett are outstanding. The extensive paper of Edmondson[6] deals with digestion, vacuum filtration, filter pressing, centrifuging and flocculation, all in an effort to solve the secondary sludge problem at Halifax (Eng.) Edmondson studied the effect of temperature and seeding to determine the minimum digestion capacity required. With mixed humus and activated sludge in proportions of 3 to 1 (dry solids), digestion effected a reduction of 28 per cent. With unheated tanks a digestion capacity equal to five months sludge production would be required which, at 80° F. could be reduced to 32 days. The sludge treated did not produce sufficient gas to maintain the desired temperatures, probably on account of the industrial waste present. Ardern and Lockett[7] reported results on mesophilic and thermophilic digestion of activated sludge. They found that addition of fresh solids up to 15 per cent aided the digestion of activated sludge. This effect was most marked with mesophilic digestion. With thermophilic digestion the reduction

in volume was about the same as with mesophilic, with a detention period about 35 per cent less. A thinner sludge resulted.

The time and rate of sludge digestion and their variations with temperature have been studied by Fair and Moore [8] in an attempt to convert data published by various authors to a comparable basis. With regard to the effect of temperature on batch digestion, three or four distinct zones of activities seem to be indicated, namely (1) thermophilic (above 42° C.), (2) intermediate (28°–42° C.), (3) temperate (10°–28°C.), (4) cryophilic (below 10° C.). The conclusion is reached that zones 1 and 3 and possibly 4 follow ordinary chemical laws, the time decreasing and the rate of digestion increasing according to the law of Arrhenius. The intermediate zone apparently does not follow the law, possibly due to the unfavorable temperature on the bacteria. A more logical conclusion would be that in this zone there is overlapping of different groups of bacteria. The optimum temperature for mesophilic digestion is set at 33° C., in agreement with Heukelekian.

The difficulty of obtaining proper balances between losses of organic matter during digestion and material in the gases formed is well recognized by those who have attempted evaluations. Larson, Boruff and Buswell [9] state that they obtained a satisfactory carbon balance with one of the two laboratory experiments performed. They stressed the accuracy of the results obtained. Each gram of volatile matter digested produced 1.33 grams of gas, increasing to 1.44 grams if the data are corrected for the $CO_2$ held in solution by the liquors, and to 1.35 grams if the solids are corrected for the probable loss of ammonium salts. The authors state that "the production of 1.44 grams of gas per gram of organic matter decomposed is to be expected from previous investigations" made by them. On the basis of several studies the data "should definitely establish the fact that the anaerobic digestion of sewage solids produces $CO_2$ and $CH_4$, the weight of which exceeds the weight of the volatile matter removed due to the reaction with water." These results and conclusions are based upon certain analytical methods the accuracy of which has not been satisfactorily shown.

Aerobic decomposition of sludge was investigated by Heukelekian.[10] He found that a 50 per cent reduction in volatile matter was obtained with fresh sewage solids aerated for 65 days; seeding the same material with aerobic sludge reduced the time to 35 days. Fat and B.O.D. reductions were greater and nitrogen reduction less with the seeded material. Material digested anaerobically was further reduced by aeration.

*Trickling Filters.*—Few important contributions have been made during the year on the mechanism of trickling filters. Studies on the function of filters reported by Gaultier,[11] based on research by Blunk of the Emscher District, indicate that with the increase in the mass of film

present in the filter the contact time of the sewage increases, and that the purification obtained is directly proportional to the volume of film. The allowable loading of the filter can be calculated from the volume of the film present. When the sewage is fresh and well aerated the amount of oxygen passing into the filter with the spray is adequate for aeration and the carrying away of gaseous products, especially $CO_2$. Temperature is an important factor, as has often been shown. Calculations show that a ripened filter operated at 15° C. can take care of 5 kg. of organic material per day for each cubic meter of film. Several sets of curves show the relations between volume of film, air requirements, contact time, sewage concentration, and the size of filter material.

No new methods of control or important contributions to the knowledge of fly breeding have been reported. Dyson and Lloyd [12] report that the most abundant species of fly present at the Leeds sewage filters is *Spaniotoma minima*, a minute black fly 1.5 mm. long, active in day time, which mates on walls, pipes and surfaces of puddles and deposits its eggs in small clusters embedded in mucus. On limestone it appears to be twice as prolific as on gravel beds. To prevent fly breeding smooth pebbles are preferred.

The life history, habits and control of that hardy perennial, the *Psychoda* fly, have been made the subject of an excellent summary by Fair.[13] The fly may hibernate in any one of its four phases; egg, larvae, pupa and adult, although in the latter case, only in the lower strata of the filters. The trickling filter provides the ideal condition of life for *Psychoda*, which lays from 10 to 40 eggs and completes a life cycle of from 10 to 16 days in warm weather. These facts sufficiently account for its distressing prevalence. Although not a biting fly, *Psychoda* may be considered a potential menace to health, justifying serious consideration of control measures.

Among such measures the various possible biological agencies offer little hope of usefulness. A voluminous literature is cited by Fair, tending to show that neither repellants nor contact agents can be effectively used for control by chemical means. Intermittent chlorination may substantially destroy the larvae by bringing about an off-season un loading of the filters, which may be otherwise unobjectionable, if not actually beneficial. Periodic flooding of 24-hour duration, as developed at Plainfield, New Jersey, has been found to be successful. Filter construction is also a control factor. Tighter walls and in particular a surface barrier of coarse gravel have been found helpful.

*Aeration and Oxidation.*—The efficiency of biological processes depends so largely upon the solution of oxygen in water that the determination of this rate is of fundamental importance. Scouller and Watson [14] have shown by laboratory experiemnts that the top portion

of the water always contains a greater percentage of oxygen than the bottom portion, whether the surface be open or covered. Oxygen was absorbed from bubble surfaces at three times the rate of absorption through the exposed surface. Kessener and Ribbius [15] calling attention to the fact that the comparison of aeration systems turned out quite differently when sewage instead of tap water was oxygenated, state that in recent experiments with sterilized sewage the oxygenation capacity of an air blowing plant was reduced by 70 per cent and the oxygenation capacity of a surface aeration plant by only 35 per cent.

Absorption of oxygen by crude sewage, effluents and activated sludge at various temperatures and pH values has been studied in the laboratory of the London School of Hygiene.[2] The Barcroft apparatus was used. The quantities of sewage used were 2 c.c. to which 1 c.c. of buffer solution was added. The rates of absorption varied considerably as the oxidation proceeded and the changes in rate were different with different samples of sewage. With effluents the differences were noticed within a few hours. The relative rates of oxidation showed that all results obtained in the Barcroft apparatus were higher than those obtained with the dilution test for B.O.D. The temperature in the apparatus was somewhat higher. Possibly the removal of $CO_2$ facilitated oxidation. The rate of oxidation of a mixture of sewage and activated sludge was greater than the sum of the rates of the individual constituents of the mixture, especially during the earlier stages of oxidation. These results are not surprising since food supply in the one and a properly balanced flora and fauna in the other sample have a pronounced effect.

The effect of pH values on the oxidation of sewage and sludge was investigated. No oxidation occurred at pH 4.0 and very little at pH 12.5. The maximum rate occurred in the pH range 6.6 to 9.0. The rates of oxidation were evidently affected by the salts in solution used for buffers. The maximum oxidation of ammonia took place in the pH range of 8.0 to 9.2; at pH 6.4 and 10.0 no appreciable oxidation occurred.

Sewage and sludge sterilized by heating or disinfectants did not absorb oxygen in the Barcroft apparatus (consisting of two flasks connected to a differential manometer), but oxidation started immediately after inoculation with certain bacteria (*Ps. fluorescens, Ps. pyocyaneus, B. coli* and *proteus*). No oxidation of ammonia occurred with these organisms. A species of a flagellate protozoa, *Polytoma uvella*, free from bacteria, brought about oxidation of sewage and sludge, but less than that of the bacteria *Ps. fluorescens* and *B. coli*.

The effect of temperature and seasons on the purification of sewage by the activated sludge process was studied by Viehl.[16] He stated that the oxidation of organic nitrogen followed the van't Hoff rule between

temperatures of 2 to 25° C. The optimum for nitrate formation was approximately 26° C. and for nitrite formation 35° C. The optimum temperature for the process was found to be about 29° C. The effect of temperature upon the reduction of organic matter was relatively important. Between 15 and 30° C. the rate of oxidation was nearly constant; at 8° C. and below, retardation occurred, while above 35° C. the rate decreased rapidly. The flora and fauna of the sludge seemed to be able to adjust themselves to low temperatures, so that after two months operation the sludge kept near 0° C. had about the same purification power as at 8° C. The median temperatures produced the most dilute sludge, containing the greatest numbers of *Sphaerotilus* and the greatest variety of species of protozoa and metazoa, while the largest numbers of organisms were noticed at the lower temperatures. Above 44°C. practically nothing but bacteria were present, with poorer purification, so that aerobic thermophilic purification could not be accomplished. Seasonal fluctuations were unimportant; the purification in summer was probably somewhat retarded because the incoming sewage was more septic than in winter. The numbers of protozoa and fungi did not vary with the seasons, but settling of the sludge was poorer in summer and fall than in winter and spring.

*Activated Sludge.*—The mass effect of return activated sludge may affect materially the rate and degree of purification of sewage. Stress has also been laid upon specific organisms present which may cause "bulking" as well as upon substances present which may upset good purification. Jan Smit [17] in a second paper on the bulking of activated sludge, reviews the opinions of several investigators and describes some interesting experiments on the so-called caustive organisms.

Acid-forming materials added to sludge showed that the pH could be lowered to 5.0 without the occurrence of bulking.

Schmiedt had previously reported that bulking occurred in the presence of 0.3 to 0.5 p.p.m. $H_2S$, but Smit added from 5 to 10 p.p.m. equivalent $H_2S$ as $Na_2S$ without causing bulking. Smit isolated pure cultures of the organism presumably responsible for the bulking (*Sphaerotilus natans*) and studied their characteristics. He found that their nitrogen requirements were slight, that they utilized glucose, levulose, lactose, saccharose, maltose, galactose, mannitol and salicin, could not utilize glycerol or arabinose, that in a medium containing glucose and an excess of calcium carbonate, the sugar fermented in a few days, and 20 per cent of the fermented sugar was recovered as acetic acid by distillation. The optimum temperature of growth was from 20 to 25° C. and the pH value 6 to 8.

The oxygen requirements of the organism were unusual, in that growth took place normally on the surface of agar plates at atmospheric

pressure, but was not retarded appreciably in a bottle completely filled and stoppered, with nearly complete exclusion of the air. Aeration, however, retarded growth.

"In view of the fact that bulking of activated sludge develops under full aeration of the liquid, and that excessive amounts of air neither prevent nor cure the disease, this behavior is rather astonishing, and seems to indicate that in sewage the oxygen is unable to create conditions of full aeration, whatever the amount of air may be."

The identification of the organism as *Sphaerotilus natans* is not established with complete certainty, and the "crucial experiment," causing the sludge disease by adding the organism to healthy sludge, has not yet succeeded, nor has it been possible to indicate the conditions that bring about an abundant development of the threads under apparently quite normal conditions. This report is illustrated with some exceptionally fine photomicrographs.

Heukelekian [18] in further laboratory studies points out the relation between the quality of the effluent and the stage of oxidation of the activated sludge.

When working with three materials, sewage alone, sewage plus activated sludge, and sludge alone in varying suspended solids concentration, it was found that in general suspended solids increased slightly with 6 hours aeration, remained constant with 12 hours aeration, and decreased with 48 hours aeration, indicating that sewage colloids are precipitated during the aeration period.

The B.O.D. and the oxygen consumed from permanganate of the various mixtures showed a continuous decrease as the aeration period increased, while the ash content of the suspended solids tended to increase slightly.

In evaluating the extent or stage of the oxidation, the author pointed out the relation between the B.O.D. and the suspended solids concentration. If the solids were all in exactly the same state of oxidation, the amount of B.O.D. required by 1 p.p.m. suspended matter would be the same in all cases, regardless of concentration.

It was found that as the suspended solids concentration increases, the amount of B.O.D. required per part suspended solids decreases, consequently the higher this ratio the lower the stage of oxidation.

Comparatively little is known about numbers of bacteria and the relation between flora and fauna in the activated sludge process. Heukelekian [19] has made an attempt to study the bacterial numbers of activated sludge mixtures and their various experimental conditions. He found that with low concentration of solids the numbers of bacteria were generally high per unit amount of suspended solids but that the

relative increase of bacteria was accompanied by a lower purification efficiency. The effect of aerating sludge mixtures of low concentration was generally an increase in bacterial numbers while in sludge mixtures of high suspended concentrations the bacterial numbers tend to decrease as a result of aeration. In another publication [20] he reported that the numbers of small protozoa decreased and the large protozoa increased as the amount of activated sludge was increased in relation to sewage.

Last year experiments were reported on the rate of oxidation of sewage solids when subjected to air without return of considerable quantities of activated sludge. Results reported by Calvert and Bloodgood [21] on plain aeration showed that composition of the sludge produced was materially different from activated sludge. The nitrogen content was lower, whereas the grease content was nearly three times higher.

Concentration of activated sludge in a settling tank, where it grows stale at a rapid rate, may affect the rate and degree of purification. This effect is most important in plants with comparatively short detention periods.

Ridenour and Henderson [22] in laboratory studies of the effect of stale return sludge on the activated sludge process, correlated the concentration of solids with the tendency of the sludge to deteriorate. The condition of the sludge was established by a determination of the 10-minute B.O.D. per gram of volatile matter. The increase of the B.O.D. was directly proportional to the concentration of the sludge. By maintaining a constant concentration of solids in the mixed liquor and varying the concentration in the settling tanks to change the 10-minute B.O.D. of the returned sludge, they found that the effect of staleness "was noticeable throughout the entire length of the aerator," as measured by the determination of the B.O.D. of the supernatant liquor, and that the decrease in efficiency was in fairly direct proportion to the B.O.D. of the returned sludge.

*Chemical Precipitation and Sludge Dewatering.*—No one has as yet presented an adequate theory of the basic phenomena involved in chemical precipitation and sludge dewatering. From time to time contributions to such a theory appear. Genter [23] has attempted to demonstrate that the well-known resistance of sewage sludge to coagulation is not so much due to the nature and amount of colloids present as to interfering soluble decomposition products produced during digestion and accumulated in the liquid surrounding the sludge particles. Ammoniacal compounds in particular react with the coagulant. The concentration of soluble decomposition products in the surrounding liquor and held by adsorption can be decreased by changing the adsorption equilibrium by elutriation. The removal of the soluble compounds of ammonia and its derivatives from sludges saves considerable coagulant. The author has not shown

that the phenomena discussed are wholly or in major part responsible for the difficulties enumerated, although he has presented evidence of value.

Results dealing with the relationship between drainability of sludge and the degree of digestion were reported by Rudolfs and Heukelekian.[25] They found that drainability increased with the increase in gas production until and shortly after the peak of gas formation had been reached. Storage decreased the drainability, while the nature of the sludge, certain industrial wastes, etc., affected the dewatering. Results obtained by Edmondson [6] on vacuum filtration of mixed secondary sludge and activated sludge alone showed cakes of 82 and 87 per cent moisture after suitable conditioning. In his experiments lime proved the best conditioning agent for mixed sludges and $FeCl_3$ for activated sludge alone. Activated sludge was not amenable to pressing, while centrifuging yielded products from unconditioned sludge comparable with those obtained by vacuum filtration from conditioned sludges. The results however were not impressive as a final product.

*Methods.*—Difficulties with B.O.D. determinations, especially varying results from duplicate samples are frequently encountered. Determinations of the B.O.D. of pure organic substances such as sugars, are apt to show variations especially when the samples are not properly seeded. Results reported by the Water Pollution Research Board [2] on the B.O.D. of sucrose solutions, incubated in tap water and without "any special inoculant" show variations from 462 to 693 parts per million. Changing the size of sample and sealing the bottles with wax did not show appreciable differences in the variations. Experiments were made with a Barcroft respirometer, consisting of two flasks connected to a differential manometer, in an effort to adapt the apparatus for B.O.D. determinations.

Analytical procedures applied to sludge are notoriously crude and have been too often neglected. In an excellent summary of the situation with regard to the volumes of sludges and to the dozen or more ratios, indices and other methods of describing volume relationships Mohlman [26] has shown the unsatisfactory status of the present situation and has proposed a sludge index in the interest of uniformity and precision. This index is the volume in cu. cm. occupied by one gram of sludge after settling 30 minutes. The volume settling from a given sample is determined as usual. The sample is then mixed and the suspended solids determined in per cent by weight. The sludge index is then the ratio of the per cent by volume to the per cent by weight. The need for such a standardizd index is shown by the conversion factors of 100, 1000, and 10,000 necessary to convert to three other indices commonly used at present.

A study of the pH in sludge by Banta and Pomeroy [27] led to the conclusion that it "is determined by the equilibrium between dissolved $CO_2$ and bicarbonate ion." The concentration of dissolved $CO_2$ is dependent upon the composition of the gas evolved and the bicarbonate by the excess of alkaline substances over the organic and fixed acids. The colorimetric pH determination may be a convenient indication of certain conditions, but is uncertain for the progress of digestion after the pH is above 6.5. The authors apparently have not considered the buffer action of materials such as phosphates, which undoubtedly are of importance.

An apparatus for the determination of dissolved oxygen in sewage mixtures has been described by Theriault and McNamee.[28] It is especially designed for determinations of low D.O. concentrations in activated sludge—sewage mixtures. The dissolved gases in the mixture are removed to a vacuum system within 15 seconds of collection and then subjected to a gas analysis. An accuracy of about 10 per cent is claimed.

## Sludge Digestion and Disposal

The year 1934 in sludge disposal was characterized by a number of new plants, by further developments in dewatering sludge on vacuum filters and by spray drying, by elutriation as a means of increasing the efficiency of sludge filtration, by an increased interest in sludge incineration, and by experimental work on the digestion of mixtures of sludge and ground garbage. As in 1933 there was continued interest in the operation of gas engines with sludge gas.

Genter,[3] Keefer [29] and also Keefer and Kratz [30] have published the results of extended experiments on the elutriation or washing of sludge as a means of reducing the amount of coagulant needed for conditioning sludge prior to dewatering on vacuum filters. Elutriation of digested sludge was found to remove some of the ammoniacal compounds of decomposition which reacted with ferric chloride. Keefer and Kratz reported that ferric chloride appeared to be the best of four coagulants tried, and that the improved operation of vacuum filters was greater for digested than for raw sludge. The cost of vacuum filtration of elutriated sludge was estimated by Keefer at $3.30 per ton as compared with $6.13 per ton for drying on open sand beds.

The combustion of screenings or sludges involves the sewage works engineer in the complexities of power-house problems, heat units, evaporation of water, etc. In addition there is a serious problem of odor control. Stilson [24] has analyzed the thermal balance in evaporation and combustion of various types of sludges, and, despite a certain weakness in some of his chemical and biological assumptions, has laid a founda-

tion, both as to manner of treatment and as to fundamental data, for a more complete theory.

He considered as successive steps: dewatering by filtration or otherwise, reducing the moisture from 95 to 75 per cent; drying to approximately 20 per cent moisture; and combustion. Only the last two steps were discussed.

In the drying stage, odor prevention is a prime consideration. The author assumed that odors evolved in the drying of fresh sludge represent the exact "materials" that would be altered during digestion of the sludge, and that such "materials" could be determined by analysis before and after digestion. "Materials," as illustrated in a specimen hypothetical analysis, were carbon, nitrogen, and fats, oils, etc., which curiously added up to 100 per cent. The same line of reasoning would make albumin much less digestible than animal fat.

Despite this attempt to base good experimental observations upon weak assumptions, the data themselves are useful if confirmed in practical operation. Drying temperatures of 95°–100°F. were recommended, with avoidance of local scorching to prevent destructive distillation. From a moisture content of 50 down to 20 per cent, which is as low as it is safe or necessary to go, it was recommended that the exhaust air be burned at 722° F. or higher. A slight degree of alkalinity and presence of iron salts were assumed to assist in odor prevention.

Most of the discussion of the incinerator or combustion stage was devoted to a demonstration of the thermal waste, of adding paper pulp to sludge. Upon the data given, pulp, on a dry basis, has a lower heat of combustion than most sludges and hence its addition is unfavorable to the balance. The practical usefulness of this section, again, is the example of computing a heat balance from data given. The discussion of this paper brought out a variety of opinion, the concensus being that filter cake sludges are best handled as garbage and burned with adequate extra fuel to guarantee complete and odorless combustion.

Experiments[31] at Chicago have indicated that the incineration of sludge cake from vacuum filters is practical and economical on a large scale. The process involves vacuum filtration, flash drying and combustion. An incinerating plant with a rated capacity of 40 tons of dry sludge per 24 hours has been approved for construction at the Calumet plant of the Chicago Sanitary District.[32] At Dearborn,[33] Michigan, a sludge incinerator has just been placed in operation with a rated capacity of 50 tons per 24 hours of filter cake having a moisture content of 65 per cent. The contract cost was $56,000.

Spray drying of sludge as tried out at Plainfield, New Jersey, was described by Downes.[34] The drying equipment comprises a spraying tower, furnace, blowers, atomizers and appurtenances. The furnace burns

sludge and soft coal, the data indicating that the sludge furnishes about one-third of the total heat.

Chamberlain [35] has discussed conditioning of sludge with various coagulants for dewatering on vacuum filters. An editorial in This Journal [36] concludes that the relative merits of open and glass covered sand beds are still indeterminate; and that vacuum filtration appears to be more expensive than drying on sand beds, but that progress in mechanical filtration appears likely. Donaldson [37] has reported the successful filtration of raw primary and excess activated sludges at Hagerstown. Dosing was found to be necessary immediately preceding the filters. Paper pulp did not appear to be helpful. The cost was given as $13.74 per ton of dry solids.

As a result of three years of experimental work at Manchester,[39] England, it was reported that equal volumes of activated and primary sludge digested readily, but that the digestion of activated sludge alone was unsatisfactory. The addition of 10 per cent of primary sludge aided the digestion of activated sludge, and 15 per cent stabilized the digestion of activated sludge. Short periods of digestion appeared to increase the difficulty of separating sludge liquor.

Keefer and Kratz [40] reported that Baltimore garbage would digest readily if properly seeded with sewage sludge. The digestion period at 28° C. was reported to be 30 to 40 days. The optimum pH was found to be 6.8 to 7.2. The digested material could be dried on sand beds. Gas production was found to be at least equal to that of sewage sludge, with an indication that the $CO_2$ content of the gas might be somewhat high.

A new caterpillar tractor equipped with side dump bins for hauling sludge from sand beds has been described by Walraven,[41] engineer at the Springfield, Ill., sewage treatment works. The bins, which are detachable, have a total capacity of 2.75 cubic yards.

Sperry [42] has used a novel tipping bucket meter for measuring sludge. He states that the meter is easily kept clean and permits a visual inspection of the sludge.

The installation of gas engines to operate on sludge gas is included in contract plans, or is seriously contemplated, for the sewage treatment plants at Washington, D. C., Coney Island, N. Y., Madison and Janesville, Wisconsin, Peoria, Illinois, Cedar Rapids, Iowa, Toledo, Ohio, Decatur and Rockford, Illinois.

## Activated Sludge

Studies of the activated sludge process proceed along three lines.

First—Investigation in the laboratory into the fundamental principles involved, in order to expand and furnish new methods of experimentation.

Second—Experiments with small units, designed to obtain basic data for the design and construction of larger plants.

Third—Study of the results of operation of full-scale plants, as a basis for improved design and more efficient operation in succeeding plants.

Thus we have a cycle, each phase of which is dependent on the other.

Much of the research of today has been made necessary by the vagaries of plant performance. Perhaps the most noteworthy proof of this statement is the study of the cause and prevention of "bulking," discussed in former reports of this committee.[43]. During the year several additional papers have appeared.

Mauzey [44] attributed bulking to the tomato seeds and peach scraps received at the Phoenix, Arizona, plant during the canning season. It was remedied by the addition of lime to aeration and sludge reaeration tanks. At Gastonia, N. C.,[45] dye wastes were assumed to be the cause. The addition of ferric chloride to the crude sewage entering the aeration tanks prevented further bulking and the plant again functioned normally.

Bulking was remedied at Glenelg, Australia,[46] by M. Garlick by reduction of incoming sewage and increase in aeration. The biochemical aspects of this problem are discussed on page 154.

The problem of diffused aeration versus mechanical aeration has been discussed by Babbitt.[47] He states that in diffusion methods, much of the power is utilized in agitating the contents of the tank, and that such agitation can be accomplished more efficiently by mechanical means. He makes favorable mention of Imhoff's method of diffused aeration combined with submerged paddles to turn the sewage. In mechanical plants he points out that the thin film of sewage exposed to the air is almost instantaneously saturated with oxygen. If this saturated film can be broken up and the liquid turned over, a constantly changing layer of unsaturated liquor is exposed to the air. This turning over and exposure to the air is essential regardless of how it is accomplished, and as evidence of its importance, Babbitt refers to the greater success of the spiral flow tank, as against similar tanks having more complete distribution of air over the horizontal area.

Kessener [48] carried on experiments in aerating tanks with windows and found that air bubbles, from diffuser plates along one side of the bottom, moved straight upward, the majority of them breaking on the surface di-

rectly above the plates; very few were carried with the revolving flow. With paddles for distributing the air, the air column was bent toward the middle of the tank, and distribution was not very good. Air bubbles produced by revolving brushes were more finely divided than with direct air. A much smaller percentage burst on reaching the surface and distribution was better. Small bubbles rose very slowly and were more susceptible to cross currents.

Adeney and Schmiedt [49] state that with increased volume of air and more vigorous ascension of the air bubbles the detention period and resultant absorption are less.

Kessener and Ribbius [15] in seeking a method for the determination of the purification capacity of an activated sludge plant, conclude that the measuring stick is the "oxygenation capacity."

Adeney and others have found that the rate of oxygen absorption from the air by water kept uniformly mixed is directly proportional to the oxygen deficiency, to the aeration area, and to a temperature function.

$$\frac{dc}{dt} = A \times 0.00594\ (T - 239)\ (C_s - C_t)$$

where

$\frac{dc}{dt}$ = rate of $O_2$ absorption from the air at time, $t$, in grams per hour per cubic meter,

$A$ = aeration area per volume of water in $m^2/m^3$ = meters,

$T$ = absolute temperature,

$C_s$ = saturation value of the water for air—oxygen at the given temperature and pressure ($g/m^3$ gms. per cu. m.),

$C_t$ = oxygen content of the water at time $t$.

Kessener and Ribbius in a test using no surface aeration, except that produced by the movements of the water itself when turned by completely submerged paddles, found a very close relationship between the actual and the calculated values of 0.280, and 0.281 and 0.280 $m^2/m^3$, respectively, against the actual natural area of 0.272 $m^2/m^3$ (the natural area being the surface area of the tank divided by the volume of the tank). Their method of procedure was to fill the tank with clean water, free the water from oxygen by chemical methods, start the aeration mechanism and then determine the oxygen at regularly timed intervals by proper sampling. The water was deoxygenated by a mixture of ferrous sulphate and sodium hydroxide.

This method is applicable when mechanical aeration is used and the air pressure is atmospheric, but aeration with compressed air complicates the problem. For compressed air systems the expression "aeration area" is insufficient and Kessener therefore uses the term "oxy-

genation capacity." The curve for oxygen absorption attains higher values when using compressed air due to the air bubbles being under higher pressure. "Since the saturation value is directly proportional to the air pressure, the theoretical pressure during aeration can be calculated from two experimentally determined saturation values. This pressure appears to exceed the barometric pressure by something less than half the head of water above the diffusers."

For direct comparison of a compressed air with a surface aeration system the $dc/dt$ must be converted to the same conditions of pressure by multiplying by $P_{760}/760$ where $P_{760}$ is the theoretical air pressure during aeration, calculated for barometric pressure 760.

Experiments with settled sewage did not show such regular oxygen absorption curves as clean water. The dissolved oxygen increased more slowly, became constant and then decreased (due to the biochemical oxygen demand).

Oxygen absorption by sewage seemed to be more unfavorably influenced by diffused air systems than by surface aeration systems.

Schmiedt,[50] experimenting with aeration of sewage in a Dywidag tank, employed varying quantities of air and aeration time. He concluded that the aeration depends upon the surface area, the temperature and the depth of the liquid. The smaller the air bubbles the more rapid he found the oxygen absorption. The oxygen absorption in activated sludge depends upon the type and concentration of sludge produced, and the degree of purification. Schmiedt concluded that purification with activated sludge is due to absorption of sewage colloids by the sludge and that such absorption depends upon the degree and time of mixing. Schmiedt would make the processes purely physical-chemical, while Kessener and Ribbius criticize his work as well as his conclusions. They hold that the process is largely one of biochemical oxidation.

At Lima, Ohio,[51] one of four aeration tanks required more air pressure than the the other three. A solution of 5 per cent sodium hydroxide (lye) was passed backwards and forwards through the filtros plates, by alternately applying and shutting off the air for 10 days. This corrected the difficulty due to clogging of the plates.

Roe [52] described the causes of clogging and presented a summary of the various practices used for cleaning air diffusers. The various methods consist of caustic, acid, or chlorine treatments, sand blasting, surface spalling, surface burning, vacuum treatment, resting, steam or water backwashing and various combinations of these procedures.

Sierp and Fransemeier [53] concluded that copper to the extent of 1 p.p.m. had no effect in activated sludge treatment. If greater amounts than this are encountered disturbances appear which can apparently be overcome by increased aeration.

At Indianapolis, Indiana,[21] the activated sludge plant was inadequate to treat the entire flow of sewage. Calvert and Bloodgood after experimenting with a one million gallon unit, changed the operation so that no sludge was returned, and the sewage received only plain aeration for a 7½ hour period. While the total flow treated was increased, and the plant effluent was not so attractive as it formerly was, the total pounds of suspended matter and B.O.D. removed were considerably increased. The character of the sludge formed was quite different, in that the solids content of the plain aerated sludge was considerably greater and such sludge contained more ether-soluble material and less nitrogen and ash than true activated sludge. No difficulty was encountered in the digestion of the changed sludge. The effect of the change in treatment was that the cost of removing one pound of B.O.D. decreased from $5.33 to $3.46, the removal of suspended solids by the plant increased 64 per cent and the removal of B.O.D. increased 43 per cent.

Schimrigk[54] placed wood shavings in the sludge activation tanks to increase surfaces for biological growth. Good results were reported.

In a paper "Settling and Compacting of Activated Sludge," Rudolfs and Lacy[55] review the findings of previous investigations, and present the following conclusions:—

(*a*) With increasing aeration temperatures the rate of settling increases. With increasing settling temperatures the rate of settling decreases.

(*b*) Pressure has little effect on settling.

(*c*) With increasing solids concentration rates of settling and compacting are retarded.

(*d*) The shape of the container makes little difference in the volume of sludge settled in 30 minutes.

(*e*) The greater the depth of the liquid the slower the rate of settling.

(*f*) The greater the angle from vertical the less volume is occupied by the sludge after 30 minutes settling.

(*g*) Prolonged aeration decreased the volume of sludge settled.

(*h*) Stirring and mixing appear to have little effect on the settling and compacting.

(*i*) Increasing septicity generally results in slower settling and compacting.

(*j*) Fresh solids added to activated sludge cause the mixtures to settle and compact at a more rapid rate than activated sludge alone.

Walter Scott[56] of Bury, England, read a paper in March, 1934, at the Institute of Sewage Purification, pointing out the troubles in sewage purification due to gas works liquors in sewage. The plant at Bury is a surface aeration plant. Gas works liquor reduced the volume treated

from 1.0 to 0.6 m.g.d. with a decidedly inferior effluent and increased the horsepower from 20 to 34 HP per million gallons.

In Germany, treatment of gas liquors has been accomplished by filtration through carbon filters, and removals from 93.5 to 96.0 per cent have been obtained. The cost of the treatment is just about offset by the sale of the recovered phenol.

Gas liquors have been reported to cause difficulties at Phoenix, Arizona.[44] The addition of lime to the aeration and sludge reaeration tanks did not correct the condition.

Experiments in England by Key and Etheridge [57] have indicated that the activated sludge removed 100 per cent of the phenol in 8 hours or less.

According to Foster and Haase [58] air, distributed in as small bubbles and as uniformly as possible, applied in sufficient quantity to bring the sewage to a strong boil, changes the phenols by polymerization to insoluble compounds, which can be removed by filtration. The temperature must be 158° F. or higher and the pH between 8.0–10.0. Such a process seems impracticable for the entire sewage flow of a city, but it might be used at the origin of the wastes.

Fischer [59] has commented on the disturbing effects of supernatant liquor added to raw sewage entering activated sludge plants.

Travaini [60] at Phoenix, Arizona, has had difficulties with supernatant liquor, and by reducing the quantity of liquor by concentrating the sludge entering the digester, he has improved the operation of the plant.

Rawn [61] has reported that septic sewage formerly reached the activated sludge plant, and did not respond readily to treatment. Chlorination produced a fresh sewage at the plant and the plant capacity was trebled.

Experiments in the United States have indicated that treatment of dairy wastes by the activated sludge process is not feasible.

Kessener [62] has made studies both in the laboratory and in actual plant practice to show that it can be and is being done by the activated sludge process, using the revolving brush aerator.

At Hamoir, Belgium, a plant was designed to treat the wastes from a plant handling 25,000 quarts of milk daily, giving a sewage flow of about 92,500 gallons. The plant has been in operation since the spring of 1932 and has been treating 37,000 gallons of sewage per day. The use of hydrated lime appears to be essential in the summer to keep down the acidity. A number of tests taken over a period of time from May 28, 1932, to September 5, 1933, indicate that the 5-day B.O.D. can be reduced from an average of 314 p.p.m. to 5.3 p.p.m.

Dr. Hamlin [63] at the 1934 fall meeting of the New York State Sewage Works Association discussed some unique features of the Johannesburg,

South Africa, activated sludge plant, where excess activated sludge was pumped to the incoming sewage one-half mile distant from the plant. This tended to deodorize the sewage and to increase the settling efficiency from 12 to 20 per cent. Another interesting feature, (determined by experiment) was that on account of the high altitude, mechanical aerating devices would operate at only 35 to 40 per cent of the normal efficiency as observed at lower altitudes.

At Velbert, Germany,[64] an activated sludge unit was installed following Emscher tanks. The air was supplied by revolving brushes of the Kessener type. The plant was designed to provide 9 hours aeration for a population of 20,000. The power to drive the revolving brushes is produced by the fall of the plant effluent.

Experimental plants are still being constructed to compare activated sludge with other forms of treatment.

The Apulian Aqueduct Commission has built a plant at Foggia, Italy,[65] and their findings covering operation results from August, 1931, to October, 1933, have been published in a report.

Three methods of activated sludge treatment operating on the same sewage will be watched with interest at the Davyhulme Plant, Manchester, England.[66] A 16 million gallon air diffusion plant, a 1 million gallon Simplex plant and a 0.6 bioaeration plant (vertical paddle wheels) will operate side by side.

### Trickling Filters

The ventilation of trickling filters has received consideration from time to time but lacks satisfactory experimental study. Levine and Goresline [67] contribute a study made upon a pair of experimental filters treating dilute skim milk. Each filter had an area of 2 sq. ft., a depth of 6 ft. and was filled with a rather tight mixture of clinkers, ranging from $\frac{5}{8}$ to 2 inches in diameter, except for the upper 6 inches which was of 2 to 4-inch material. The filters were provided with ventilating ports which could be closed, the outlets being trapped. A 2 per cent skim milk mixture was applied at the rate of 0.5 m.g. per acre per day. This constituted a rather heavy loading, but the purification was adequate, with ventilation, but failed with resulting pooling on the surface when ventilation was discontinued.

Payrow [68] has tested the tentative procedure adopted by a committee of the American Society of Civil Engineers, Sanitary Engineering Division, for determining the soundness of trickling filter media, *i.e.*, resistance to disintegration by alternate freezing and thawing, simulated in the test by crystallization of sodium sulphate. He finds that under controlled conditions, 20 successive treatments by the test are equivalent to 100 freezings, each in 24-hour cycles. The temperature of the

test must be standardized, however, and in view of other necessary refinements the author prefers actual freezing and thawing in a refrigerator fitted with a heating system and an automatic control of the cycle which, under these conditions, can be reduced to eight hours.

(See also references to filters in section Chemistry and Biology, p. 151.)

## Chlorination and Allied Processes

Chlorine continues to serve as a highly useful chemical for various applications, temporary and permanent, in sewage disposal practice. Aside from its growing use as a sewage disinfecting agent it has now other important applications: (*a*) prechlorination to alleviate or eliminate odor nuisances by suppressing bacterial activity and consequent septization of sewage; (*b*) for the production of "home-made" ferrous or ferric chloride by passing strong chlorine water upward through iron scrap in towers; (*c*) for the production of a cheap ferric iron coagulant—chlorinated copperas—by chlorination of ferrous sulphate solutions produced continuously; (*d*) for the partial reduction of biochemical oxygen demand, retardation of the degradation of effluents with resultant stream loading; (*e*) control of aquatic growths in streams below sewage treatment works.

During the year a compendium on sewage chlorination has appeared in the American Public Health Association's Committee report "Sewage Chlorination." This report (Committee Chairman Langdon Pearse) is the most valuable reference work which has yet been published on this subject. It was distributed by the A. P. H. A. to members of its Engineering Section; by the Chlorine Institute, Inc., and Wallace and Tiernan Co., Inc. Copies may be obtained upon request to these agencies.

*Crude Sewage Chlorination.*—But few attempts have been made to chlorinate crude or coarsely screened sewage except as an emergency or temporary measure. At Duluth, Minn., however, in the interval before completion of its treatment works (sedimentation, digestion, chlorination), the crude sewage is being chlorinated in a novel manner. The screened sewage enters a holding (contact) tank providing 30 minutes of detention after application of the chlorine. To preclude solids deposition and to provide continuous and intimate contact of solids with the chlorinated liquid, the tank contents are continuously turned over by revolving paddle wheels—an adaptation of the flocculator utilized in water coagulation and chemical precipitation processes.

*Prechlorination.*—For increased efficiencies in disinfection and improved clarification (septic tanks excepted) it has been thoroughly established that the practice of prechlorination yields results superior to

chlorination of the effluent, particularly whenever sewage temperatures are conducive to septicization.

*Partial Chlorination.*—Studies reported by Rudolfs [69] and co-workers point to the efficacy of fractional chlorination (a satisfaction of but 50 per cent and upwards of the chlorine demand), for disinfection efficiency, provided: (*a*) the sewage or effluent is fresh at the point of chlorination; (*b*) long periods of contact (one hour and upward) are available; (*c*) efficient chlorine distribution is assured. Not only are saprophytic (oxygen depleting) organisms destroyed and regrowths curbed, but remarkable reductions in *B. coli* numbers are observed, viz.: satisfaction of 50 per cent of the chlorine demand reduces *B. coli* by 95 per cent after one hour, sometimes in a shorter period.

*Odor Control and Sewer Preservation.*—Chlorination for odor control continues in service on the Los Angeles County trunk sewers, where no less than eight chlorinator stations are maintained and 1500 to 1800 lbs. of chlorine are applied daily. This treatment controls odors and, more important, makes it possible for the activated sludge plant to handle the entire flow to the plant because of a fresher, less toxic sewage which is more amenable to aerobic treatment.

After several years of careful observation, the American Concrete Pipe Association has, in 1934, rendered the opinion (Association Bulletins) that partial chlorination seems to be a real and permanent solution to the prevention of hydrogen sulphide production in sewers with consequent damage to concrete and masonry sewers, the process now being recommended and endorsed by the Association as a relief measure.

Once more the value of prechlorination ahead of Imhoff tanks, as against chlorination of effluent for disinfection or odor control, has been established—at Lyons, N. Y., by the Research Committee of the New York Sewage Works Association; at Stamford, Conn., by the State Department of Health [70] and the municipality.

*Ferrous Chloride in Odor Control.*—A newer development in effective, economical odor control is that put to use first at Oklahoma City, Okla., by Scott and Darcy. Early attempts to make ferric chloride by discharging chlorine water upward through a tower filled with iron scrap to produce ferric chloride for coagulation in chemical precipitation processes led to the idea of the simpler, more controllable process of making ferrous chloride solution only, by the same scheme, and continuously discharging it into a long odor-producing sewer carrying packing house wastes plus domestic sewage. The overall efficiency, with less chlorine consumption, was thereby materially increased by the dual effect of disinfection and the affinity of the sulphides for the iron which resulted in non-volatile sulphide formation. The fact that the iron has no tendency to combine with the organic compounds, as has chlorine,

tends to make the iron effective throughout the entire sewer length and also through the Imhoff tanks.

The process of using the iron scrap tower has since been effectively utilized at Lincoln and York, Neb., and Princeton, New Jersey.

*Chlorinated Copperas.*—Several places have adopted chlorinated copperas for coagulation, including Plainfield, N. J., now combining chemical precipitation with secondary biological treatment.

At Liberty, N. Y., chlorine and copperas were determined to be the most economical and effective sewage coagulants, as based on a large scale demonstration, made under the supervision of the State Department of Health. Here the chlorine was added to the sewage; the copperas solution was applied a few seconds later, and this was followed by a small dosage of lime.

Demonstrations of dewatering of digested sludge on vacuum filters at Baltimore indicated that chlorinated copperas was the most economical of the iron coagulants.

*Sludge Thickening.*—To reduce liquid loadings on digesters, sludge thickening is receiving increasing attention. Heavy chlorination of sludge has made it possible to procure high concentrations of crude, or of mixtures of crude and activated sludges. The high germicidal value of the liquor drawn from the concentration tanks makes it valuable for return to the incoming crude sewage. This scheme has not affected subsequent digestion of mixed settled and activated sludges at Newark, New York. A similar scheme is in use at Butler, Pennsylvania. The method of concentrating wasted activated sludge developed by Goudey at Los Angeles on a small test plant scale has proven efficacious at Phoenix, Arizona,[60] making it possible to operate the plant without the odor nuisance attendant upon activating high-sulphate sewages with insufficient air capacity. At Phoenix the tap water in the thickening tank (clarifier) is chlorinated to maintain a slight residual chlorine at all times in the effluent. The thickened sludge (3 to 5 per cent solids) is transferred to the digesters and thus the amount of supernatant liquor to be handled is greatly reduced and the digesters are less disturbed by the liquor added. The small chlorine application merely maintains the sludge in a stable rate, which allows the necessary holding and sludge depth for effective thickening. Excessive chlorine application produces peptization or bulking of the thickened activated sludge, as was proven at the Hagerstown, Maryland, plant, during the summer of 1934. The thickening scheme will be further tested during the summer of 1935 because the problem is largely one of summer conditions, due to septicity of the mixed sludges in the preliminary tanks.

*Sphaerotilus Control.*—In activated sludge plants deficiency of aeration capacities resulting from heavy organic loads result in a defective

sludge impregnated by *sphaerotilus* and allied organisms. Bulking and loss of sludge over the effluent wiers results and the thin sludge creates added difficulties when pumped to digesters. At Lima, Ohio, such difficulties were corrected by adding a small continuous dosage (1 to 2 p.p.m.) of chlorine to the returned sludge. With the killing off of the offending *sphaerotilus*, the sludge returned to its normal condition only to bulk again with cessation of chlorination. The Lima method and results are to be published.

*Industrial Wastes.*—Studies made at Durham, North Carolina, have shown that chlorination of certain wastes discharged by six textile and dyeing plants made them more amenable to treatment. It has been decided to require textile mill operators to chlorinate their wastes before discharging them to the municipal sewer system, for the sole purpose of relieving the loading on Durham's new activated sludge plant, which now operates as an air-blowing chemical treatment plant to avoid patent infringement for the duration of the activated sludge patents.

*Prechlorination with Chemical Precipitation.*—It has been amply demonstrated at Freeport, Long Island, Liberty, New York, and Birmingham, Alabama, that prechlorination of sewages subjected to chemical precipitation with iron salts is a highly important step in the process, in order to secure effective precipitation and to avoid reduction of the iron.

*Reducing Chlorination Costs.*—Aside from efficient distribution of chlorine, long contacts, and the lime-chlorine combination, there appears another scheme successfully used by several plants having to pay for water used in chlorinator operation. Small centrifugal pumps have been installed to deliver sewage plant effluent to operate the injector on the chlorinators. The dribble of water entering the tray of the machines is purchased. The scheme is practical and economical.[71]

## Chemical and Mechanical Processes

Chemical treatment of sewage has continued to grow in importance both as a primary process and as an agency supplementary to plain sedimentation or existing biological plants. There are now in operation, or assured of construction, approximately 50 plants in the U. S. which employ chemical precipitation alone or in conjunction with secondary biological treatment. Chemicals are used for only a few months in the year at most places. Experimental work is going forward at many points wherein the value of chemical treatment is being tested and improvements are being developed.

Of outstanding interest is the decision[72] to incorporate chemical treatment in the proposed works of the Minneapolis-St. Paul Sanitary

District for an estimated average sewage flow of 134 m.g.d. Here it was shown by careful studies of oxygen balance in the Mississippi River that plain sedimentation, with 33 per cent B.O.D. removal, would suffice for 90 per cent of the time. For the remaining 10 per cent of the time, possibly four consecutive months in worst years, and none at all in some years, 70 per cent B.O.D. removal was estimated to be sufficient. On this basis the new works are being designed for plain sedimentation, with chemical precipitation provided to increase the efficiency when needed. The sludge will be digested, dewatered on vacuum filters, and the sludge cake for the time being will be used for fill, with incineration as the future goal. The particular type of chemical treatment has not been stated, although cost estimates were set up on the assumption that ferric chloride would be used.

New York City is planning to install at Coney Island a 35 m.g.d. plant employing plain sedimentation in winter, with chemical precipitation and chlorination in summer. An iron salt will be used for precipitation, with or without lime as required. Filtration of the effluent is being considered as a future extension.[78]

The Dearborn, Michigan, plant, employing the Laughlin process, continues to be watched with considerable interest as the first practical-scale plant in daily operation which was designed expressly for continuous chemical treatment. Tests of operation by Dr. A. M. Buswell, referred to in last year's report of the Research Committee [43] were made in October and November, 1933, on domestic West Side sewage separately from the sludge of the larger East Side works. Operating and analytical data were reported [73] throughout a 30-day test. A few of the more important data are:

| Item | Ave. | Range of 87% of the Values | % Removal |
|---|---|---|---|
| Flow m.g.d. | 2.4 | 1.88–3.28 | |
| Suspended solids | | | |
| Sewage | 227 | 74–400 | |
| Eff. | 18 | 7–25 | 92 |
| B.O.D. | | | |
| Sewage | 113 | 73–170 | |
| Eff. | 28 | 20–39 | 75 |
| Suspended solids removed (analysis) | 209 p.p.m. equivalent to 1740 lbs. per mg. | | |
| Total solids removed (as filter cake) | 2100 lbs. per mg. | | |

The average chemical doses were, lime 220 lbs. (as CaO), iron salt 86 lbs. (as Fe), and paper 154 lbs. per million gallons. The results from use of ferric chloride were practically identical with those from use of ferric sulphate, when both were computed to the same basis of the metallic iron content, namely, about 10 p.p.m. Fe.

The author attributes the apparent inconsistency in the suspended solids data to analytical error. It would seem more likely that it represents the effect of coagulation upon the filtrability of colloidal and finally suspended matter. If so it is an important characteristic of a sewage and suggests an attempt to standardize a test to determine "coagulable colloidal matter."

At Perth Amboy, New Jersey, the second plant-scale Laughlin installation is nearing completion. It includes improved flocculating arrangements and facilities for handling and feeding reagents.

At Birmingham, Alabama, the Shades Valley plant, initially described by H. H. Hendon, Sanitary Engineer for Jefferson County,[74] has attracted wide attention. Hendon, in January, 1935,[75] gave more information regarding this installation, which was started in operation in June, 1934, and has had about two months' operation with chemicals. The plant was laid out with unusual flexibility of operation to permit either plain sedimentation or various combinations of single-stage or double-stage operation, with or without return of chemically precipitated sludge. The precipitant used is chlorinated-copperas. At the New York meeting, Hendon reported best results from series operation of the two settling tanks, with primary settling followed by chemical application to flocculators ahead of the secondary tank, and with return of all chemical sludge to the raw sewage. In treating a weak sewage 100 p.p.m. suspended solids and 80 p.p.m. B.O.D., he obtained 90 per cent and 87 per cent removal, respectively. The corresponding chemical doses were reported as 70 lbs. chlorine and 440 lbs. copperas, per million gallons (10.5 p.p.m. Fe) at a chemical cost of $5.40 per million gallons treated. A portable experimental chemical plant designed by Hendon to test the stronger sewages of the Birmingham District showed a removal of approximately 95 per cent, in suspended solids and B.O.D., with little increase in chemical doses over those required at the Shades Valley plant.

The Guggenheim process, as now being promoted, differs from the process demonstrated in New York City and tested at the North Side Works of the Sanitary District at Chicago. The process now offered has been simplified by omission of the zeolite filtration of the clarifier effluent, omission of ammonia recovery and omission of regeneration of the iron. Two plants of 3.0 m.g.d. capacity each are proposed for Raleigh, North Carolina. A guarantee to the city calls for 80 per cent average removal of both suspended solids and B.O.D.

An unusual type of treatment is that incorporated in the 1.0 m.g.d. plant now under construction for the Incorporated Village of Great Neck, Long Island, expected to be placed in operation in the summer of 1935. Screened sewage will be dosed with lime, or lime and chlorine. Provision is made for later use of ferric salts if found desirable. The clarified sewage from settling tanks will be handled by two vacuum filters using paper pulp as a filter medium after the manner of Rockville Center, described in the last report of this Committee.[43] The filter effluent will be chlorinated. As at Rockville Center, the pulp cake from the "clarifier" filters will be repulped, washed and reused, with the washings returned to the settling tanks. A third vacuum filter is provided to dewater all settling tank sludge after conditioning with lime, or lime and paper pulp. Sludge cake from the third filter will be incinerated or used for fill.

At Winston Salem, North Carolina, studies are under way involving larger applications of lime as the precipitant and recarbonation and secondary settling of the first-stage effluent to increase removals of organic colloids. The plan is to economize on chemical cost by dewatering and incineration of all sludge with recovery of lime.

At Waco, Texas, an air blowing scheme, involving contact surfaces in an aerating channel, with one hour aeration, is being tried in conjunction with iron coagulants in moderate dosages, to agglomerate the light and finely divided organic floc particles produced in the decolloidizing operation. Economy in chemicals and power is sought in the combination process, which appears to produce a high degree of purification with minimum variation in chemical requirement and costs.

*Vacuum Filters for Sludge Dewatering.*—At Hagerstown the operations of vacuum filters for dewatering mixed activated, fresh solids and screenings, subsequent to changes made in sludge conditioning were reported by Donaldson.[37] Substitution of two mixers operated in series for ferric chloride and lime, in the order named, resulted in raising the filter yield from 0.65 to 1.97 lbs./sq.ft./hr. of dry sewage solids. Sludge conditioning chemicals during this period averaged 9.4 per cent CaO and 5.5 per cent $FeCl_3$ on the dry solids basis. Hagerstown now uses anhydrous ferric chloride for sludge conditioning, having earlier employed lump ferric chloride and later ready prepared solution shipped in carboys.

The results of extensive vacuum filter tests at Cleveland, Ohio, have been reported by Jones.[70] The average yield from Imhoff sludge conditioned with 8.5 per cent ferric chloride was 5.7 lbs./sq.ft./hr.; separate digested sludge conditioned with 7.7 to 8.7 per cent ferric chloride gave an average yield from 7.5 (July and August) to 5.0 (November) lbs./sq.ft./hr. The author concludes "at least 8.0 per cent of ferric

chloride will be required to produce an output of between 4 and 5 pounds per square foot of filtering area per hour on a year round basis."

A valuable comparison of the costs of sludge disposal by digestion and sand beds versus vacuum filter was made by Ferguson, Wisely, Greeley and Velzey.[27] Their conclusions, based on the study of six Illinois plants, were that mechanical dewatering of sludge was less economical than digestion and sand-bed drying for plants serving a population under 50,000, whereas the two methods compared favorably for populations of 100,000 or over.

Keefer[29] in a similar comparison relating to Baltimore conditions, where both methods have been subjected to careful investigation, found that vacuum filtration of digested sludge was superior to the older methods. He gives the cost per ton of dry solids by air drying at $6.13, compared with $4.50 for vacuum filtering of unelutriated sludges; and $3.30 with elutriation. A more extensive discussion of this work is given by Keefer and Kratz.[30]

*Heat Drying and Incineration of Sludge.*—The Sanitary District of Chicago has continued the large-scale experiments on drying and incinerating sludge, referred to in last year's report of this Committee. In 1934 a new type of dryer and incinerator was operated at the West Side Works.[28] The new dryer consists of two-stage pulverizing mills (recently changed to a single stage), through which sludge cake is passed, together with heated air from heat-exchangers in the furnace. The dried sludge is separated from vapors and gases in cyclones, from which the solids are removed and burned as pulverized fuel. All vapors and gases are passed through the hottest zone of the furnace, thus eliminating odors, and the heat is recovered in heat exchanges. A small amount of coal is burned as auxiliary fuel. The final product is an inorganic ash.

The process has been adopted for disposal of sludge at the new Calumet Treatment Works of the Sanitary District, with provision for drying and incinerating 40 tons of sludge (dry basis) per day.

At Dearborn, Michigan, a Nicholas-Herreshoff dryer and incinerator, installed late in 1934, for final disposal of the sludge cake from vacuum filters, previously disposed of by dumping, is now in operation. No results have been published covering the brief period of service to date.

Designs for the two plants at Raleigh, North Carolina, include a combination dryer and incinerator for the vacuum filter cake.

The spray dryer installation at Plainfield referred to in last year's report of this Committee, and described by Downes[29] has for several months been in regular service. Operating results and costs are not yet available.

## Stream Pollution

The Illinois River is probably unique in the extent and intensity of the studies that have been made of its pollution and self-purification. Pearse [79] presents a valuable summary of this long series of studies, a summary containing much material of general and fundamental value in addition to its local interest. Since the beginning of the Chicago diversion projects the river has shown progressive deterioration both in the intensity of the effects and in the distance to which they could be traced. In 1905 evidence of the effect of the drainage canal was measurable as far as 150 miles below. Since 1926 when the program of remedial treatment was begun there has been a continuous improvement in river conditions although lessened and partially masked by the decrease in the lake diversion.

Reaeration has been studied under various conditions. Data given show the results of a single exposure over a dam at Marseilles where there is an average improvement of 2.85 p.p.m. and a maximum (summertime) improvement of 4.3 p.p.m. of dissolved oxygen. It has appeared to the reviewer that during the long controversy over this situation too little attention has been paid to the possibilities suggested by this single series of observations. A rough computation indicates that the amount of oxygen made available by the dam at Marseilles is from 3 to 5 times that initially available in the form of the dilution water from Lake Michigan. The author points out however that the lengthened time of passage resulting from decreasing lake diversion results in a foreshortening and apparent concentration of the effects.

The real problem has been to finance a tremendous sewage treatment program, sufficient to provide a safe balance with available dilution resources, which have been greatly reduced by order of the Supreme Court.

In this connection, but from a somewhat broader viewpoint of conservation of all stream resources, Streeter [80] has admirably summarized our present situation with regard to "Tendencies of Standards of River and Lake Cleanliness." His report is so condensed that an adequate review would necessarily encompass the entire paper. The tendency noted in each of his subdivisions, nuisance prevention, fish life, water supplies, swimming pools and bathing beaches, and shell fish areas are in the direction of lower limitations of permissible pollution and the search for a more rational basis of experimental facts upon which to construct an acceptable standard. His illustrative cases range from that most unscientific of our so-called standards, those relating to bathing places, with a 30-fold range among various proposals, to the carefully formulated standards of permissible loading on water filters, based upon such satisfactory experimental work as to justify their acceptance with every confidence.

The late Professor William T. Sedgwick was fond of describing standards in sanitation as "devices to save lazy minds the trouble of thinking," which well describes the situation of his day, when a standard was generally no better than a pure guess by one worker easily seized upon, quoted and requoted by others until it assumed the semblance of authority. Something of this same method still remains in certain fields of modern sanitation but with the development of standards committees in our great national organizations and the consequent critical discussion of current methods, together with the accumulation of scientific data upon which to base these discussions and a formulation of a joint opinion, standards in the true sense of general agreement of opinion by expert and experienced technicians, are assuming an increasingly important rôle.

Warrick [81] discusses the important question of a common yardstick with which to compare the injurious effects of various industrial wastes upon streams. Obviously this measure must be in terms of the use of the stream and of the character of the possible nuisance resulting from its pollution. Thus the wastes of a chemical plant containing phenol might have an "equivalent population" value negligibly small if expressed in terms of B.O.D., much higher if in terms of specific toxicity to fish, and still higher in terms of phenol as affecting the water supply of a downstream community.

This point of view is emphasized in more detail by Hubbs [82] with reference to fish life and by Soper in the discussion of a paper by Phelps [83] on the pollution of New York Harbor. The general rule is self-evident but perhaps needs to be definitely formulated. Any given waste or resultant condition of pollution is equivalent to any other only as regards that characteristic which is inherent in the yardstick or test by which they are compared.

Notwithstanding this limitation it is becoming increasingly frequent and helpful to convert industrial wastes to their "equivalent populations" on the basis of the B.O.D. test, equivalence in this case referring, by the rule just stated, only as to de-oxygenation of the stream. Warrick gives a short list of such values in various types of pulp and paper mills and of milk handling depots. Calvert [84] reports the results of a similar study, of brief duration but apparently carefully done, including a laundry, creamery, dairy, canning plant, starch factory, five slaughter houses, a paper board mill and a garbage reduction plant, all at Indianapolis. The value of such a study in sewage works design, as well as in stream pollution prevention, is well indicated in the author's data. The B.O.D. of the city sewage indicated a population of 587,000 in 1933, against an actual connected population of 341,000. The "equivalent populations" of the major wastes investigated totalled 268,000,

making the combined effective population at the plant 609,000 which is within 4 per cent of the measured value.

It is of significance to note in this connection also that the industrial wastes of Indianapolis contribute about 44 per cent of the B.O.D. to be treated in the disposal plant. Pearse [79] finds a similar figure (43%) for the proportionate contribution of the industrial wastes of the Chicago Sanitary District and some recent (as yet unpublished) data reported by Gould indicate an excess of about the same order in the apparent contributing population in the New York Harbor area.

In a paper read before the New York State Sewage Works Association Phelps [83] has summarized the various studies of the pollution of New York Harbor and adjacent waters since 1910. He deals primarily with the problem of formulating the quantitative aspects of residual dissolved oxygen as affected by the inter-related factors of existing pollution, tidal circulation, influx of aerated waters from the sea, sound and river, and reaeration. A formulation made in 1910 based upon mean annual conditions was in sufficient agreement with the experimental observations of the next few years to justify the general method employed and encourage further attempts at refinement. A more complete formula includes the variable flow of the Hudson developed in 1933, is in much better agreement with the data of the present 23-year record and describes the annual fluctuations about the mean trend. There seems to be a still further systematic source of error in that the errors of the formula from the experimental observations now appear to have a cyclic tendency with something like a 23-year period. The possibility of a major tidal period of about this length is suggested.

Streeter [85] has made a further contribution in the field of the mathematical analysis of bacteriological phenomena, to which he has given such serious thought during past years. It is one of the outstanding advantages of the work at the Cincinnati station that its continuation from year to year, in ever widening circles of interest, has led to the accumulation of a mass of homogeneous data in which it is becoming more and more profitable to search for generalizations. The present paper is a research (literally), of this sort.

It has been observed that bacterial death rates, measured from station to station along the Ohio River, parallel the corresponding rates obtained by incubation of the same waters in the laboratory under low temperature conditions, but during the summer months there are discrepancies of such an order as definitely to suggest an undiscovered variable. The author attributes this to the results of sedimentation, which is most active during the warm, low-water periods. Having available the recorded data upon the turbidity of these waters at various

stations he has undertaken to correct the bacteriological data upon the assumption that the effect of sedimentation on the bacteria is measured quantitatively by its effect upon turbidity. This correction brings the bacterial findings into much closer harmony with the laboratory data and the author concludes that the residual discrepancies "appear to have been due largely to the effect of progressive changes in suspended matter resulting from sedimentation."

Streeter likewise reviews and extends his earlier work on the com posite logarithmic death rate curve which, rather than the simple classical curve of Chick, seemed best to picture the situation in a stream with mixed flora. Finally he demonstrates and applies a correction term to cover the initial increase in numbers commonly observed in polluted streams and heretofore rather embarrassing and hence generally overlooked by the mathematically-minded biologist. The correction term derived is again in harmony with certain recorded facts on the growth of bacteria but, what appears to be of more fundamental significance, the resulting equation now assumes a form identical with that known in mechanics as the damped, aperiodic wave. The author points out that this is the more striking in that the earlier data of Butterfield and Purdy (see this review for 1933), with mixtures of pure cultures of bacteria and protozoa, gave curves closely simulating periodic damped waves. He believes the single-crested, aperiodic wave, represents the more rapid and complete adjustment to a new set of conditions, possible only in the mixed fauna and flora of the stream, whereas two pure cultures, one depending upon the other for food, necessarily approach equilibrium by a series of diminishing oscillations.

Applying his deductions to the practical matter of determination of the B.O.D. in the laboratory the author makes two postulates, namely:

(1) The rate of change in B.O.D. is proportional to the generation rate of the bacteria;

(2) This generation rate is roughly proportional to the total number of bacteria present, as determined by the plate count.

From (1) it follows that the total reduction in B.O.D. during any time interval is proportional to the number of bacteria generated in that interval and from (2) this number will be proportional to the summation of the varying bacterial count through the same interval. It is unnecessary, however, to perform this integration as Streeter does to arrive at the conclusion that, in the presence of a bacterial population decreasing logarithmically, the well-known logarithmic decrease in the concentration of B.O.D. will follow. One may however question whether this agreement justifies the postulates.

The first of these is satisfactorily based upon the earlier work of the

Cincinnati group but the second seems to the reviewer to be inconsistent with that work. A constant population level, for example, is quite compatible with a very low rate of generation, as was found to be the case when such populations had reached their self-imposed upper limit and it is equally compatible with a very rapid rate of generation in the presence of a high death rate due to the activity of the protozoa.

This conclusion seems to have been arrived at by the author by other reasoning, for he finds that when he applies this technique to the earlier stages of the incubation period, during which bacterial multiplication is active, the agreement between the well-known laboratory curve of B.O.D. reduction and his mathematical curve is unsatisfactory. He is inclined to ascribe the discrepancy to an error in postulate [85] but it is more readily traced to the lack of agreement which we have reason to believe exists between present bacterial population and rate of generation.

Public interest in the control of stream pollution was at a high level in 1934 as evidenced by discussions in the daily press and in technical journals.[86] Interest was heightened by the report of the National Resources Board to the President, Part III of which contains recommendations on water planning for dealing with the problem.[87]

An important source of stream pollution affecting many water supplies was attacked during the year, using C.W.A. funds to seal abandoned coal mines. Unfortunately the funds were cut off at the end of ninety days before the problem was adequately handled. The progress made is outlined by Tisdale,[88] who shows that 25 per cent of the abandoned mines in West Virginia were sealed, 10 per cent in Pennsylvania, and 2 per cent in Ohio. In West Virginia enough work was done to improve the conditions of some streams so that cattle again drink from them, fish life increases and water purification plant operators report the pH of the river water approaches the neutral point in some streams.

Experimental work carried on by Moon and Hamilton in cooperation with the Bureau of Fisheries seems to justify the conclusion that fresh water mussels are of no value in the destruction of bacteria in water.[89]

These conclusions are not identical with those drawn by English workers on purification of salt water mussels (reported by Dodson, His Majesty's Stationery Office), who reported that mussels placed in tanks of contaminated sea water effected a bacteriological betterment both of the water and of the mussels, due apparently to the digestion of bacteria by the shellfish and to the entanglement of bacteria in the slime of pseudo-feces. The results of unpublished experiments by Fisher with sea water soft clams tends to confirm the English conclusions.

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# MEASUREMENT OF INTENSITY AND CONCENTRATION OF ODORS ASSOCIATED WITH SEWAGE TREATMENT PROCESSES

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The great sanitary awakening which swept England early in the nineteenth century and spread thence over the civilized world was, in many ways, an awakening of the esthetic senses of man—notably of his sense of smell. The developments of sewerage systems, safe sewage disposal and adequate sewage treatment, which were part of this important sanitary movement, were actuated in no small degree by an aroused olfactory consciousness. In the middle of the past century, we are told, improper sewerage had so polluted the Thames River that a distinguished foreign visitor commented that the cry of the day seemed to be "India is in revolt and the Thames stinks." It is hard to tell which circumstance was more disturbing to the British public, the mutiny in provinces far beyond the seas or the odors arising from the once proud stream washing the shores of the Houses of Parliament. Here frightened legislators resorted to the use of curtains saturated with chloride of lime to mask the stenches wafted into the parliamentary chambers from the river, and travellers went far out of their way to avoid passing over the bridges spanning the fetid floods of the lower Thames.

The early days of sewerage in America present strikingly similar situations. To verify them, we may turn to one of the Annual Reports of the Board of Health of Boston as quoted by Eliot C. Clark [1] in his classic description of the Main Drainage Works of the City of Boston (1885).

> Complaints of bad odors have been made more frequently during the past year than ever before. They come from nearly all parts of the city, but especially and seriously from the South and West Ends.
>
> Large territories have been at once, and frequently, enveloped in an atmosphere of stench so strong as to arouse the sleeping, terrify the weak, and nauseate and exasperate everybody. It has been noticed more in the evening and by night than during the day; although there is no time in the whole day when it may not come. It visits the rich and the poor alike. It fills the sick chamber and the office. Distance seems to lend but little protection. It travels in a belt half-way across the city, and at that distance seems to have lost none of its potency, and, although its source is miles away, you feel sure it is directly at your feet. . . .
>
> The sewers and the sewage flats in and about the city furnish nine-tenths of all the stenches complained of. They are much worse each succeeding year; they will be much worse next year than this. The accumulation of sewage upon the flats and

about the city has been, and is, rapidly increasing, until there is not probably a foot of mud in the river, in the basins, in the docks, or elsewhere in close proximity to the city, that is not fouled with sewage.

This vivid word picture of early conditions in Boston—similar situations arising subsequently in other populated areas—forces us to recognize the control of odors as one of the motivating forces of sewerage and may help us to understand the opprobrium which men attach by inheritance to regions in which sewage disposal works are situated, even though modern works can be operated in such a way that they do not create an aërial odor nuisance. In the words of Watson,[2] "It would be a Herculean task to convince the public that a works for sewage treatment can be other than a nuisance, and to obtain without opposition an acceptable site for a great works near a town is almost unthinkable."

Objection to odors associated with decomposition or decay is a deep-seated protective mechanism of man which has its roots in the primary function of his sense of smell to protect him against unfavorable environmental substances, especially against harmful foods. It is true also that only a few decades ago medical practitioners held that the spread of certain infectious diseases was traceable to miasmas arising from decaying matter. This ghost which frightened our forefathers has not been laid in spite of the pronouncements of science based on the germ theory of disease. We know that infectious disease is not carried on the wind and that most sewage odors, with exception of the odors of certain poisonous gases, such as hydrogen sulphide, are not associated with harm. Yet our objection to sewage odors remains unsuppressed, and it may be true that our physiological aversion to them may be reflected in a lowered health tone when we are exposed to them for protracted periods of time and in high concentration. Bad odors must, therefore, be classed as nuisances and it behooves the designer and manager of sewage disposal works to become more familiar than he has been in the past with the sources of sewage odors, and particularly to inquire into the physical magnitudes involved in odor nuisances. These magnitudes have gone unrecognized because we have not had at hand a means for measuring the intensities or concentrations of odors generated in sewage treatment and disposal.

For some time the problem of odor measurement has occupied the attention of the Laboratory of Sanitary Engineering at Harvard, and it is the purpose of this paper to present certain measurements of odor intensities emanating from sewage treatment processes and to describe briefly the apparatus and procedures developed to make these measurements possible.

## Physical and Physiological Factors

In view of the nature of the subject it may be well to consider first as briefly as possible some of the physical and physiological factors involved.

Odors, unlike light and sound, are not radiant in character and do not disperse from a given center in all directions. They are sensed as material particles that are carried into the nasal chamber and may be transported on the wind for many miles in a definite direction. The sense of smell is so acute in detecting the presence of odor particles that ordinary physical and chemical methods of analysis at our disposal will not record the magnitudes of many odorous substances sensed. Until more sensitive physical or chemical methods of analysis are available, the human nose must therefore continue to be relied upon to detect the presence of most odors. As we shall see later, it is possible, however, to aid the nose in determining, or at least circumscribing, the intensities of the odors observed.

The smallest amount of an odorous substance sensed by the human nose is called the "threshold value" of the odor. Expressed in grams of odorous substance per milliliter of air this threshold value is called an "olfacty." The smallest distinguishable difference in odor strength is designated the "threshold difference." Use of this term is somewhat misleading, since experience indicates that the magnitude of this difference changes with the concentration of the odorous substance;—in fact that it is proportional to the concentration. Hence, "threshold ratio" would be a better term. According to this observation, the sense of smell, like the other human senses, apparently obeys the Weber-Fechner law. This law, enunciated in part one hundred years ago, states that constant fractional increments in stimulus are required to produce equal increases in sensation, the assumption being that perceptible differences in sensation are equal amounts of sensation.

The threshold ratio of odor sensation appears to vary for different substances and may vary for different observers as well. Ratios of 1.24 : 1 to 1.62 : 1 are reported in the literature, but the subject has not been adequately studied to fix definite limits or values. As a first approximation readily attained by observers, the senior author [3] has previously suggested working with a ratio of 2 : 1. This implies that one should be able to distinguish between successive odor concentrations that are progressively twice as great as the preceding one.

## Measurement of Odor Intensities

All methods of odor-intensity measurement so far proposed are based on the principle of diluting the odor, directly or indirectly, with an

odorless fluid until the threshold value is reached. An odor in the gaseous or vaporous state, for example, would be diluted with odor-free air until the odor is just perceptible. The concentration of the undiluted odor may then be expressed in terms of the ratio of the volume of undiluted sample to the volume of the diluted sample. If, for example, this ratio is found to be 1 : 8, we may report the odor concentration as 8 times the threshold value or as 8 olfacties.* In doing so we must recognize, however, that unless we know the composition of the odorous substance, we cannot state how many grams of substance are present in one milliliter of air. Such knowledge is really implied when odor concentrations are expressed in terms of olfacties. This attempt at physical quantitation of odor concentrations reflects only indirectly the physiological response to odors of different concentration. Expressed in physical units, for example, the difference in intensity of an odor of 128 olfacties when compared with an odor of 64 olfacties would appear to be very much greater than the difference in intensity of an odor of 2 olfacties compared with an odor of 1 olfacty. Yet, in the light of the Weber-Fechner law, the difference in physiological response to each pair of odors would be essentially the same.

In order to stress the physiological basis of odor measurement the senior author [3] has suggested the use of a geometric, or ratio, scale based on a threshold ratio of 2 : 1 and related to the olfacty scale as follows:

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Odor concentration in olfacties: | 1 | 2 | 4 | 8 | 16 | 32 | 64 | 128 | etc. |
| Odor intensity in pO values: | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | etc. |

The physiological odor values are preceded by the symbol pO because they represent the power to which the threshold ratio of 2 : 1 must be raised to obtain the odor concentration in terms of olfacties. Thus pO $7 = 2^7 = 128$. It should be noted in connection with the preceding discussion that odor concentrations of 128 and 64 olfacties differ in pO value by one unit (7–6) just as odor concentrations of 2 and 1 olfacties differ in pO value by one unit (2–1). In a general way therefore the olfacty scale may be said to measure concentration of odorous substance, the pO scale intensity of odor or degree of odor response. The mathematical relation between odor power, or pO, values and olfacties may be expressed as follows:

$$\log (\text{olfacty}) = 0.301\ (\text{pO value})$$
$$\text{pO value} = 3.32 \log (\text{olfacty})$$

* Spaulding [4] has used the term "threshold number" instead.

## The Osmoscope or Odor Observer

Measurement of the intensity or concentration of odors in the gaseous or vaporous state may be accomplished most directly by the air-dilution method, *i.e.*, by diluting the odor-containing atmosphere with odor-free air, until the threshold value is reached. Developmental forms of the instruments employed by the authors for this purpose have been described previously in publications [3, 5, 6] from their laboratory. In order to make the present paper more complete in itself the two instruments now in use in the laboratory are shown in Figures 1 and 2.

Figure 1 illustrates the twin-sphere osmoscope. This is essentially

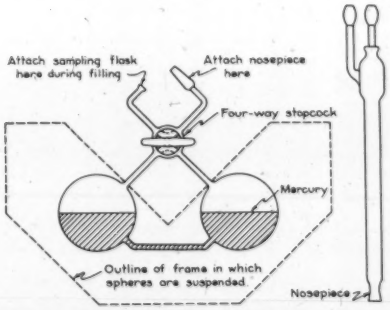


Fig. 1.—Twin-sphere osmoscope.

a spherical gas burette, which permits progressive air-dilutions of the odor drawn into the instrument by operating a four-way cock and tilting the frame in which the spheres are suspended. Dilution is carried on in steps. Successive dilutions stand in a ratio of 2:1, and the number of dilutions recorded thus equals the pO value. The odor is observed through a glass nose-piece that is fitted onto the instrument. Mercury is employed as the displacing liquid. Disadvantages of the apparatus are the relatively large surface of glass and mercury in contact with the odorous atmosphere, and the fatiguing requirement of observing odors of relatively high intensity before the threshold dilution is reached. The chief advantage is the unlimited range of dilutions that can be carried out by means of this instrument.

Figure 2 outlines the telescoping osmoscope in which two tubes, sliding over a third, open or close ports or orifices through which varying mixtures of odor and odor-free air are drawn into the observer's nose by light sniffing. The instrument shown has a dilution range of 1:2 to

1:64, *i.e.*, pO 1 to pO 6. This limitation in range of dilutions is a disadvantage of the instrument, but it can often be overcome by combining the air-dilution method with the water-dilution method. In the latter, the odor-containing liquid is diluted with odor-free water until the threshold value is reached. If the pO value exceeds 6 but is less than 12, one volume of the liquid should be diluted with 63 volumes of

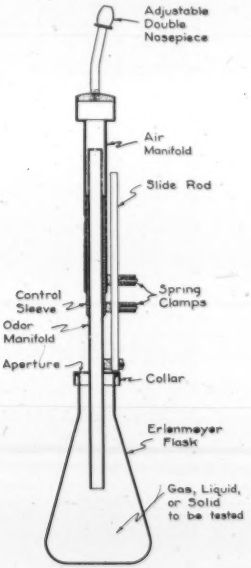


FIG. 2.—Telescoping osmoscope.

odor-free water before the osmoscope is used. If the pO value lies between 13 and 18 a second water dilution of 1:64 should be performed, etc. Odor-free water may be prepared by boiling distilled water or treating distilled or tap water with activated carbon. The chief advantage of the telescoping osmoscope is the possibility to proceed directly to the threshold dilution and avoid fatigue of the olfactory nerves. Also manipulation is simple and more rapid than with the twin-sphere osmoscope, and the individual dilutions can be observed as often as desired without interfering with the normal test procedure.

## Some Observed Odor Intensities or Concentrations

During the past year the opportunity has presented itself to measure the intensities or concentrations of odors associated with certain sewage treatment processes. While the major study has been confined to odors of sludge gases evolved during the batch digestion in the laboratory of sewage solids at different temperatures, there have been obtained also certain figures of the odor-producing potentiality of other treatment processes in existing plants. Some of these values have been published before [5] but are repeated to permit comparisons.

*Odor of Fresh and Stale Sewage.*—In order to observe the effect of age on the odor intensity of sewage, a two-gallon sample was collected from a sewer draining a residential district. About half of this sample was permitted to remain in the two-gallon glass-stoppered bottle (Sample A). The remainder was employed to fill glass-stoppered bottles of about 250 ml. capacity (Sample B). All samples were kept at room temperature. At intervals, generally of about a day, the odor intensities of Sample A and of Sample B were determined. For this purpose Sample A was thoroughly shaken before the air overlying the sewage was drawn into the twin-sphere osmoscope for observation; subsequently one of the B samples was transferred to a stoppered bottle about three times larger than the sewage volume and thoroughly shaken before the air in contact with the sewage was drawn into the twin-sphere osmoscope for measurement of odor intensity. The results presented in Table I

Table I.—*Odor of Fresh and Stale Sewage*

| Age of Sewage Hours | Odor Intensity—pO Value | | Odor Concentration—Olfacties* | |
|---|---|---|---|---|
| | Sample A | Samples B | Sample A | Samples B |
| 0 | 6 | 6 | 64 | 64 |
| 19 | 6 | 6 | 64 | 64 |
| 43 | 7 | 7 | 130 | 130 |
| 71 | 8 | 8 | 260 | 260 |
| 95 | 8 | 8 | 260 | 260 |
| 120 | 8 | 9 | 260 | 510 |
| 144 | 9 | 10 | 510 | 1000 |
| 168 | 8 | 10 | 260 | 1000 |
| — | — | — | — | — |
| 219 | 8 | 9 | 260 | 510 |
| 243 | 7 | 10 | 130 | 1000 |
| 267 | 7 | 10 | 130 | 1000 |
| 293 | 7 | 10 | 130 | 1000 |
| 309 | 8 | 11 | 260 | 2000 |

* These values may vary by ±25 per cent.

show, therefore, the change in odor intensity of more or less aerated and of unaerated sewage. The odor values for Sample A represent the accumulation of odors during the interval between samplings (about one day); the values for Samples B represent the accumulation of odors from the beginning of the test.

Jones [7] has described the odor of fresh sewage as "a smell combining that of dish-water, soap suds, gasoline, body wastes, flavored with occasional characteristic smells from industry." This is a description of odor which in its imagery appears to rival that of Mrs. Cratchit's plum pudding in Dickens' "Christmas Carol."* The quality of the odor of the freshly-collected sewage fitted Jones' description admirably. As time wore on, however, the dominant odor became that of hydrogen sulphide. Sample A retained a small amount of dissolved oxygen, while Samples B became truly septic. The sludge which settled from Sample A became black and left a clear supernatant liquid. Samples B retained their gray hue. So far as the conditions of test permit generalization, it will be noted that the more-or-less aerated sample doubled its odor concentration about every forty hours for approximately three days when four times the original value was attained, after which the odor remained at substantially the same magnitude for a week before decreasing by 50 per cent towards the end of the test. Samples B continued to double their odor concentration about every forty hours for approximately six days, the general maximum odor intensity (pO 10) observed after this time corresponding to an odor concentration of 1000 olfacties. All of the odor values observed were sufficiently strong to be called objectionable.

*Odor Survey of an Activated-Sludge Plant.*—The results of an odor survey of a diffused-air activated-sludge plant are presented in Table II.

TABLE II.—*Odor Survey of an Activated Sludge Plant*

| Source of Odor | pO Value | Olfacties† | Dilution† Required to Reduce Odor to Disappearance |
|---|---|---|---|
| Raw Sewage | 5 | 32 | 64 |
| Effluent of Aërated Skimming Tank | 4 | 16 | 32 |
| Effluent of Primary Settling Tank | 5 | 32 | 64 |
| Effluent of Activated Sludge Tank | 3 | 8 | 16 |
| Effluent of Final Settling Tank | 3 | 8 | 16 |
| Screenings | 5 | 32 | 64 |
| Return Activated Sludge | 1 | 2 | 4 |

* "The pudding was out of the copper. A smell like a washing day! That was the cloth. A smell like an eating-house and a pastry-cook's next door to each other, with a laundress next door to that! That was the pudding."

† These values may vary by ±25 per cent, and it is assumed that one dilution beyond the threshold dilution will cause the odor to become non-detectable.

In each case the odor was observed by shaking a sample of the material in a stoppered container and observing the odor of the supernatant atmosphere by means of the telescoping osmoscope. The values obtained reflect the odor-producing capacity of the process or the potential pollution of the atmosphere. This method of measurement appeared to be a more logical approach to the problem than determination of the odor actually present in the atmosphere overlying the plant, which depends so greatly on prevailing atmospheric conditions. A quantitative study of the effects of different atmospheric conditions should, however, be made to complete the picture.

The odor values observed at the activated sludge plant under consideration are not very high. The incoming sewage was quite fresh The odor intensity of the screenings equalled that of the flowing sewage The aerated skimming tank destroyed or swept out about half of the odor of the entering sewage. New odors were generated, however, during primary sedimentation. Three-fourths of these were removed in the activation units. Final settling did not increase the odor of the applied sewage. The plant itself is not considered a nuisance in the vicinity. An odor with pO value of 5—the maximum observed—is sufficiently intense, however, to force itself upon the observer's attention when the nose is brought close to the sample.

As to the quality of the odors, it was typical of sewage, except that of activated sludge. The latter had a pleasant earthy odor of low intensity. Parenthetically, a suggestion of studying the odor test in connection with other indications of the condition of activated sludge presents itself.

*Odor Survey of a Trickling-Filter Plant.*—As shown in Table III, an odor survey of a trickling-filter plant yielded values very similar to those obtained for the corresponding stages of the activated-sludge plant. Sedimentation, however, reduced the odor instead of increasing it. This

TABLE III.—*Odor Survey of a Trickling-Filter Plant*

| Source of Odor | pO Value | Olfacties* | Dilution* Required to Reduce Odor to Disappearance |
|---|---|---|---|
| Raw Sewage | 5 | 32 | 64 |
| Effluent of Primary Settling Tank | 4 | 16 | 32 |
| Effluent of Trickling Filters | 3 | 8 | 16 |
| Effluent of Final Settling Tank | 3 | 8 | 16 |
| Raw Primary Sludge | 4 | 16 | 32 |

* These values may vary by ±25 per cent, and it is assumed that one dilution beyond the threshold dilution will cause the odor to become non-detectable.

may be due to the fact that the basins in question are drawn down and thoroughly cleaned once in two weeks whereas the tanks at the activated sludge plant are provided with mechanical scrapers and remain in continuous operation. Passage through the trickling filter cut the odor concentration of the applied sewage in half, and there was no rise in concentration in the final settling tank. The odor intensity of the raw sludge equalled that of the flowing sewage. Odors of raw sewage prevailed as far as the trickling filter. The filter effluent, however, had an earthy or humus-like odor.

Attached to the plant under consideration are a number of intermittent sand filters that receive the overflow from the primary settling tanks. The effluent from one of these beds that had been heavily overloaded during the preceding winter showed an odor greater than pO 6 in intensity. Some hydrogen sulphide was present. It is evident that the bed had lost its oxidizing power. The surveys of the plants were made in the early spring.

*Odors of Sludge Gases.*—The results of measurements of odor intensities of sludge gases are summarized in Table IV. In view of the wide range of intensities encountered, the twin-sphere osmoscope was employed in evaluating these intensities, and measurements are subject to the errors of this instrument.

Gas samples were analyzed during the progress of digestion, the degree of digestion accomplished at the time of observation being expressed in terms of per cent completion of gasification. The sludges studied were produced by plain sedimentation and were seeded with the residues of previous digestions of sludges at the same temperatures. Hence the conditions recorded are presumably characteristic of normal digestion at the temperatures in question. Information on odors generated during thermophilic digestion is not as complete as for the lower temperatures because digestion in the thermophilic range was well advanced before the decision was reached to make odor measurements on the sludge gases.

Inspection of Table IV shows a wide variation in odor intensities. The pO values range from 2 to 38; the corresponding olfacties from 4 to $2.8 \times 10^{11}$. We shall note first of all a general tendency for odor intensities to increase with temperature. This becomes more evident when the weighted average intensity of the odor is ascertained. Values of this weighted average are given at the bottom of the table on the basis of carrying digestion, as measured by gasification, to 90 per cent completion. These weighted averages may, furthermore, be considered to represent the odor intensity that might be expected to obtain with continuous digestion. The trend towards higher odor values is shown graph-

TABLE IV.—*Intensity and Concentration of Odors of Sludge Gases Evolved during the Digestion of Sewage Solids at Different Temperatures*

| 15° C.–59° F. | | | 20° C.–68° F. | | | 25° C.–77° F. | | |
|---|---|---|---|---|---|---|---|---|
| % Digested | pO Value | Olfacties | % Digested | pO Value | Olfacties | % Digested | pO Value | Olfacties |
| 4.5 | 12 | $4.1\times10^{3}$ | 4.7 | 8 | $2.6\times10^{8}$ | 7.9 | 7 | $1.3\times10^{2}$ |
| 14.0 | 8 | $2.6\times10^{2}$ | 11.1 | 12 | $4.1\times10^{2}$ | 15.8 | 4 | $1.6\times10$ |
| 20.0 | 5 | $3.2\times10$ | 28.0 | 6 | $6.4\times10$ | 23.7 | 5 | $3.2\times10$ |
| 27.7 | 3 | 8 | 36.4 | 3 | 8 | 32.7 | 4 | $1.6\times10$ |
| 37.4 | 2 | 4 | 43.2 | 3 | 8 | 41.5 | 3 | 8 |
| 43.8 | 3 | 8 | 53.2 | 3 | 8 | 47.4 | 4 | $1.6\times10$ |
| 53.5 | 3 | 8 | 61.0 | 3 | 8 | 55.0 | 3 | 8 |
| 63.7 | 2 | 4 | 75.0 | 3 | 8 | 68.0 | 4 | $1.6\times10$ |
| 73.6 | 2 | 4 | 80.5 | 3 | 8 | 75.4 | 4 | $1.6\times10$ |
| 84.1 | 2 | 4 | 89.2 | 3 | 8 | 82.7 | 3 | 8 |
| 89.3 | 2 | 4 | 95.2 | 2 | 4 | 88.6 | 2 | 4 |
| — | — | — | — | — | — | 94.7 | 2 | 4 |
| * | 4.1 | $1.7\times10$ | * | 4.7 | $2.6\times10$ | * | 4.2 | $1.8\times10$ |
| 30° C.–86° F. | | | 35° C.–95° F. | | | 40° C.–104° F. | | |
| 9.0 | 10 | $1.0\times10^{3}$ | 8.7 | 17 | $1.3\times10^{5}$ | 9.5 | 18 | $2.6\times10^{5}$ |
| 14.9 | 10 | $1.0\times10^{2}$ | 14.6 | 11 | $2.0\times10^{3}$ | 15.3 | 15 | $3.3\times10^{4}$ |
| 20.3 | 6 | $6.4\times10$ | 19.8 | 7 | $1.3\times10^{2}$ | 20.0 | 26 | $6.7\times10^{7}$ |
| 26.6 | 7 | $1.3\times10^{2}$ | 26.6 | 10 | $1.0\times10^{3}$ | 28.8 | 12 | $4.1\times10^{3}$ |
| 33.7 | 8 | $2.6\times10^{2}$ | 33.7 | 7 | $1.3\times10^{2}$ | 34.9 | 8 | $2.6\times10^{2}$ |
| 48.1 | 6 | $6.4\times10$ | 40.9 | 8 | $2.6\times10^{2}$ | 41.6 | 8 | $2.6\times10^{2}$ |
| 56.3 | 4 | $1.6\times10$ | 45.5 | 5 | $3.2\times10$ | 48.7 | 8 | $2.6\times10^{2}$ |
| 65.4 | 5 | $3.2\times10$ | 55.4 | 5 | $3.2\times10$ | 55.1 | 7 | $1.3\times10^{2}$ |
| 78.4 | 5 | $3.2\times10$ | 62.6 | 6 | $6.4\times10$ | 60.0 | 7 | $1.3\times10^{2}$ |
| 85.3 | 5 | $3.2\times10$ | 68.8 | 5 | $3.2\times10$ | 72.0 | 9 | $5.1\times10^{2}$ |
| 91.2 | 3 | 8 | 74.7 | 4 | $1.6\times10$ | 78.6 | 8 | $2.6\times10^{2}$ |
| 95.8 | 3 | 8 | 89.1 | 3 | 8 | 84.7 | 6 | $6.4\times10$ |
| — | — | — | 96.0 | 3 | 8 | 92.2 | 5 | $3.2\times10$ |
| — | — | — | — | — | — | 98.0 | 5 | $3.2\times10$ |
| * | 6.5 | $9.0\times10$ | * | 7.6 | $2.0\times10^{2}$ | * | 11.2 | $2.3\times10^{2}$ |
| 45° C.–113° F. | | | 50° C.–122° F. | | | 60° C.–140° F. | | |
| 20.0 | 13 | $8.2\times10^{3}$ | 73.2 | 10 | $1.0\times10^{3}$ | 33.5 | 19 | $5.2\times10^{5}$ |
| 26.1 | 18 | $2.6\times10^{5}$ | 84.0 | 15 | $3.3\times10^{4}$ | 42.4 | 20 | $1.1\times10^{6}$ |
| 32.9 | 20 | $1.1\times10^{6}$ | 89.8 | 10 | $1.0\times10^{3}$ | 54.8 | 38 | $2.8\times10^{11}$ |
| 40.7 | 8 | $2.6\times10^{2}$ | 95.6 | 6 | $6.4\times10$ | 70.0 | 17 | $1.3\times10^{5}$ |
| 50.6 | 8 | $2.6\times10^{2}$ | 100 | 3 | 8 | 76.0 | 35 | $3.4\times10^{10}$ |
| 64.8 | 11 | $2.0\times10^{3}$ | — | — | — | 83.0 | 35 | $3.4\times10^{10}$ |
| 72.4 | 9 | $5.1\times10^{2}$ | — | — | — | 90.0 | 30 | $1.5\times10^{9}$ |
| 78.0 | 7 | $1.3\times10^{2}$ | — | — | — | 95.2 | 16 | $6.6\times10^{4}$ |
| 84.1 | 6 | $6.4\times10$ | — | — | — | 99.8 | 10 | $1.0\times10^{3}$ |
| 89.0 | 5 | $3.2\times10$ | — | — | — | — | — | — |
| 100 | 2 | 4 | — | — | — | — | — | — |
| * | 10.9 | $1.9\times10^{3}$ | * | 14.6 | $2.5\times10^{4}$ | * | 24.6 | $2.5\times10^{7}$ |

* Weighted average to 90 per cent digestion.

ically in Figure 3 and may be described approximately by the following equations:

$$\frac{pO_2}{pO_1} = 1.047^{(t_2 - t_1)} \quad \text{or} \quad \log \frac{pO_1}{pO_2} = 0.020\ (t_2 - t_1)$$

$$\frac{pO_2}{pO_1} = 1.026^{(T_2 - T_1)} \quad \text{or} \quad \log \frac{pO_2}{pO_1} = 0.11\ (T_2 - T_1)$$

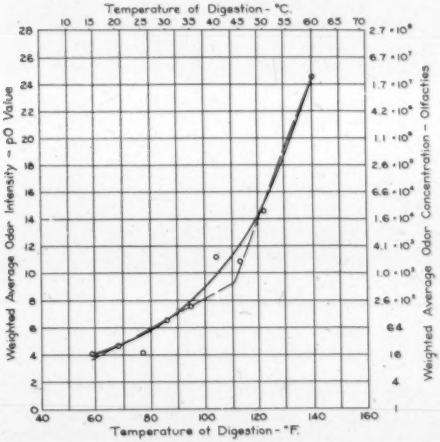


FIG. 3.—Weighted average intensity and concentration of odors of sludge gases evolved during the digestion of sewage solids at different temperatures.

The subscripts 1 and 2 refer to two different temperatures of incubation, and $t$ and $T$ are respectively the temperatures expressed in degrees centigrade and Fahrenheit. The limits of these equational generalizations are those of the experiments. The weighted average odor intensities range from pO 4.1 at 15° C. (59° F.) to pO 24.6 at 60° C. (140° F.); the corresponding odor concentrations range from 17 to $2.5 \times 10^7$ olfacties. The great increase in odor-producing power in the thermophilic range was observed by Rudolfs [8] in his first experiments on high-temperature digestion and led him to conclude that it constituted an almost insuperable handicap of the process. Rudolfs, however, had no means for recording the intensities of the odors produced. The rise in odor concentration with temperature can probably be explained for the mesophilic range (15 to 35° C., or 59 to 95° F.) by the shift in equilibrium

between the concentration of the odor-producing substances and the concentration of the decomposable substances; in addition, by the increase in vapor pressure. This explanation cannot be extended to the thermophilic range, however, unless it is assumed either that the concentration in odor-producing substances is greatly increased as a result of changes in the character of the digestion processes, or that the odoriferous substances produced have lower threshold values than those associated with mesophilic digestion. The measurements obtained, therefore, support the theory that the processes of decomposition which take place in the thermophilic range are different in nature from those obtaining at lower temperatures. It is obvious that the equations presented do not reflect these explanations. They are purely empirical.

The maximum odor intensity observed by the authors is recorded in the pO value of 38, which was reached when digestion of sludge at 140° F. was about half complete. The odor concentration of $2.8 \times 10^{11}$ olfacties is so large as to seem improbable. It may be well, therefore, to compare this value with that assigned to known odoriferous substances. As recorded by Henning,* Hermanides has determined the threshold value for skatol as about $4 \times 10^{-13}$ grams per liter. The vapor density of an odoriferous substance may be approximated by the equation:

$$D_t = \frac{M}{22.4} \times \frac{273.1}{273.1 + t}$$

where $D_t$ = density of vapor at $t°$ C. and 760 mm. pressure in grams per liter; for skatol $D_{25} = 5.35$ g.p.l.

$M$ = molecular weight of the substance.

If we assume * that skatol is the active odor-producing substance in the sludge gas and the gas is assumed * to contain 0.1 per cent by volume of the vapor of this substance, the content by weight is 0.0053 grams per liter of gas. Dilution by $2.8 \times 10^{11}$ times will reduce the concentration of the skatol to $\frac{0.0053}{2.8 \times 10^{11}} = 1.9 \times 10^{-14}$ grams per liter. This is somewhat lower than the threshold value given by Hermanides, but is still of the same order of magnitude. At such high dilutions the precision of the twin-sphere osmoscope is probably $\pm 4$ pO values which would account for the discrepancy. Adsorption of odoriferous substances on the walls and mercury of the osmoscope during initial operations and return of the adsorbed substances to the air at higher dilutions will increase the pO value reported.

Release of 100 ml. of the gas under consideration in a large and draughty four-story building brought complaints from all quarters.

* These assumptions are made to illustrate the possible magnitudes involved. They are not based on experimental findings.

This is not surprising when it is realized that this amount of gas is sufficient to impart a very strong odor (pO 8) to more than a billion times this volume of air.

Among odor-producing substances likely to be formed during sludge digestion, we may list hydrogen sulphide, the related mercaptans, and the indol family. Most of these compounds may be considered as intermediate products of the decomposition of albuminous material. With the exception of hydrogen sulphide, they are probably converted by decomposition into simpler and less odoriferous substances. Since digestion progressively destroys the albuminous substances and their intermediate decomposition products, the odor content of the gas evolved from the digesting materials may be expected to diminish. Inspection of Table IV will show that there are such general trends towards lower odor intensities as digestion progresses. These trends are shown more clearly in Figure 4, prepared by plotting odor values of certain temperature groups at fixed digestion percentages obtained by straight-line interpolation between observations. The temperature groups of 15 to

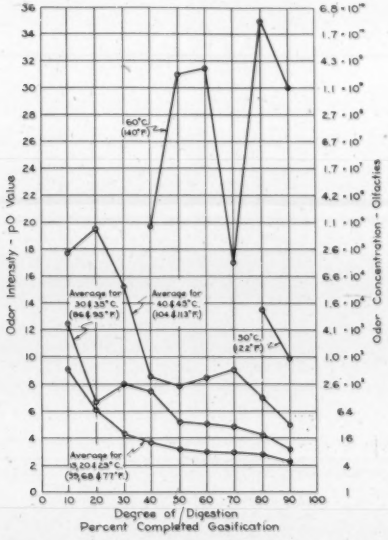
Odor Intensity - pO Value
Odor Concentration - Olfactles
Degree of Digestion
Percent Completed Gasification
60°C (140°F)
Average for 30 & 35°C. (86 & 95°F)
Average for 40 & 45°C. (104 & 113°F)
50°C. (122°F)
Average for 13, 20 & 23°C. (55, 68 & 77°F)

FIG. 4.—Changes in odor intensity and concentration of sludge gases evolved during the digestion of sewage solids at different temperatures.

25° C. (59 to 77° F.), 30 to 35° C. (86 to 95° F.) and 40 to 45° C. (104 to 113° F.) were selected in accordance with information on characteristic rates of digestion included in a previous publication by the authors.[10] Plotting of the course of odor intensity during digestion at individual temperatures would have obscured the diagram. The information on the odor of sludge gases evolved at 50 and 60° C. (122 and 140° F.) was inadequate for group presentation and is included in Figure 4 on an ungrouped basis. There is, in addition to the general trend towards lower intensities, an apparent secondary rise when gasification is about 70 per cent completed. The significance of this rise, if true, remains to be determined.

*Odors of Digested Sludge.*—At the completion of digestion, the sludges were permitted to stand in stoppered containers for a week or more at a room temperature of 25° C. (77° F.). They were then shaken vigorously to promote the transfer of odoriferous substances into the gaseous phase, and the odor intensity was observed by means of the telescoping osmoscope or the twin-sphere instrument. The results obtained are summarized in Table V.

TABLE V.—*Intensity and Concentration of Odors Emanating from Sewage Sludges Digested at Different Temperatures*

| Digestion Temperature | | pO Value | Olfacties* |
|---|---|---|---|
| ° C. | ° F. | | |
| 15 | 59 | 5 | 32 |
| 20 | 68 | 5 | 32 |
| 25 | 77 | 5 | 32 |
| 30 | 86 | 5 | 32 |
| 35 | 95 | 5 | 32 |
| 40 | 104 | 5 | 32 |
| 45 | 113 | 5 | 32 |
| 50 | 122 | 8 | 260 |
| 60 | 140 | 12 | 4100 |

* These values may vary by ±25 per cent.

The values obtained are of interest as an indication of the odor to be expected when digested sludge is drawn onto a drying bed, or is otherwise brought into contact with the atmosphere. There was no measurable difference in the odor intensities of the sludges digested at temperatures of 15 to 45° C. (59 to 113° F.), the so-called mesophilic range. The pO value was 5. This is higher than the figures observed for the

gases produced towards the end of digestion and may be attributed to the vigorous shaking of the sludge before conducting the test. The sludges produced by thermophilic digestion are much stronger in odor. As previously indicated, this may be due either to production of greater quantities of the same odoriferous substances that are generated at lower temperatures or to creation of products with lower threshold odor values. There is evidence of a difference in quality as well as in quantity of odorous materials at the higher temperatures, both in the gas and in the sludge itself. In addition to the fecal or putrid odors there are garlic odors that are most persistent. No attempt was made to describe the quality of the odors observed according to the schedule suggested by Crocker and Henderson.[11] The goaty or caprylic odors are so dominant that differentiation would appear to be most difficult. In observing them, we readily agree with Kipling's British soldiers: "No! you won't 'eed nothin' else, but them spicy garlic smells. . . ."

## Summary and Conclusions

The limited measurements of odor intensity and concentration associated with sewage treatment processes presented in this paper may be summarized as follows:

| Source of Odor | pO Value | Olfacties | Character of Odor |
|---|---|---|---|
| Raw Sewage—Fresh | 5–6 | 32–64 | dishwater |
| Raw Sewage—Stale | 6–11 | 64–2000 | putrid, $H_2S$ |
| Screenings—Fresh | 5 | 32 | putrid |
| Effluents from Biological Treatment Works | 3 | 8 | dishwater and earthy |
| Plain Sedimentation Sludge | 4 | 16 | fecal |
| Activated Sludge | 1 | 2 | earthy |
| Sludge Gases −15 to 60° C | 4.1–24.6 | $17–2.5\times10^7$ | putrid |
| Digested Sludge −15 to 60° C | 5–12 | 32–4100 | tarry to putrid |

All of these values need corroboration, and the list of processes examined should be expanded to give information on other types of sewage treatment and other sources of odor. The high intensities of odor associated with thermophilic digestion explain why it is possible to create at sewage works noxious odors that will travel considerable distances on the wind or envelop a whole region with smell on a sultry day when the "ceiling" of the odors is low.

Nothing has been said about the control of odors at sewage works. It stands to reason, however, that ability to measure odor intensities presents in itself a means for advancing the solution of this important problem.

Recognition of the geometric nature of odor response is helpful. If, for example, ventilation of a given amount is found to reduce the odor intensity from a pO value of 10 ($1.0 \times 10^3$ olfacties) to one of 9 ($5.1 \times 10^2$ olfacties), it follows that in order to decrease it to, let us say, pO4 the amount of air moved must be increased by $2^{10} \div 2^4 = 2^6 = 64$ fold $\left(\frac{1.0 \times 10^3}{1.6 \times 10} = 64\right)$. This geometric variation in ventilation requirements for odor control has been confirmed by the authors' colleague, C. P. Yaglou, in studies of body odors and room ventilation. The quantity of chlorine, permanganate, ozone, activated carbon or other deodorant required may presumably be gaged in a similar way from the results of single tests.

The hope is expressed that sewage works managers will interest themselves in measuring the odors produced at their plants not only that our knowledge of the field may thereby be increased, but also that we may learn to consider in terms of factual measurements the complaints of odor nuisance which may be received. It is conceivable, furthermore, that odor measurements may indicate immediately and simply, whether or not the different processes of treatment are functioning properly.

The osmoscopes developed in the authors' laboratory are comparable in their basic concept with the grease-spot photometer employed by Bunsen to measure the intensity of a light source. This photometer used the human eye to gage light intensity by reducing illumination to the fundamental value of a standard candle intensity. The osmoscopes, analogously, rely on the human nose to evaluate odor intensity by reducing odor concentration to the fundamental value of the threshold, or standard, intensity. There have been great advances in light measurement since Bunsen's day, and it is to be expected that there will be similar advances in odor measurement in the future.

In presenting these first steps in the measurement of the intensity and concentration of odors associated with sewage treatment processes and, in expressing these measurements in numbers, the authors clearly recognize the limitations of the procedures and instruments employed. They ask their readers to bear with them in the expectation that, by opening up this field to thought, able men will be stimulated to develop more precise means of measurement and expression. Both measurement and expression in numbers are needed if our knowledge of, and means for, dealing with this important phase of sewage treatment are to be advanced.

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# NOTES ON SEDIMENTATION *

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Sedimentation of solids of low specific gravity, suspended in a viscous fluid, has been a subject of discussion for many years. It is the purpose of this paper to develop some empirical equations, based on experimental work, which are of some value in design of settling tanks for sewage, and to make a partial analysis of the use of model basins for predicting the performance of the full sized basins.

## Technical Literature

In the design of sedimentation basins probably more use is made of Hazen's [1] theory than of any other. Hazen chose fifteen sets of conditions and discussed the theoretical time required for various percentages of removal of solids for each set of conditions. His conclusions were based on the fact that the solid particles were so widely separated that each particle settled at its own rate according to what was called its "hydraulic value."

Pearl [2] has set up an expression for the theoretical attraction between the mass of a particle of sediment and the sides of a circular container, and has attempted to show that the particle is attracted to the side of the vessel while the mass of the earth causes it to settle downward through the liquid.

Morrill [3] recommends the use of models in the design of sedimentation basins and shows that in order to have dynamic similarity between a model and a prototype "$n$" times as large in each linear dimension, the velocity in the full size structure must be $\sqrt{n}$ times that in the model. The same relation holds for the detention period.

Schroepfer [4] shows by computations from Stoke's Law that the effect of variations in specific gravity of the liquid due to temperature changes is small, especially where the specific gravity of the insoluble solids is fairly high. Variations in viscosity are much more important, the rate of settling at 30° C. being 2.3 times the rate at 0°. The specific gravity is considered the most important factor but the concentration of particles in suspension is shown to have a decided effect. Flocculation is thought to be of considerable importance in sewage sedimentation but of little consequence in the sedimentation of granular material.

* Presented at the Eighth Annual Conference of the Pennsylvania Sewage Works Association, State College, Pennsylvania, June 29, 1934.

Lunnon [5] discusses in detail the forces acting on a solid sphere settling through a liquid. He presents a curve showing the relation between Reynold's number of the sphere (obtained by multiplying the velocity, $V$, of the sphere by its diameter, $d$, and by the density of the fluid, $\delta$, and dividing this product by the viscosity of the fluid, $\mu$) and the Resistance Coefficient (which is the value obtained by dividing the force, $F$, on the sphere, by the density of the fluid, $\delta$, and by the square of $V$ times $d$). This curve is shown in Fig. 1.

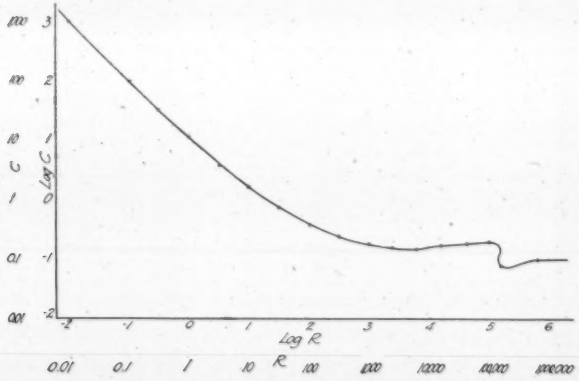


FIG. 1.—The relation between Reynolds number $R$ and coefficient of resistance $C$ plotted on a logarithmic scale.

$$R = \frac{Vd\rho}{\mu}, \qquad C = \frac{F}{\rho V^2 d^2}.$$

Babbitt and Schlenz [6] give some experimental results obtained by using varying concentrations of sewage solids in basins of different depths and detention periods. These data show the effect of the concentration of solids and of varying specific gravities. Some experimental runs were made using sand, coal and sludge as solids, and an empirical formula was derived for the particular conditions of the experiments.

The sedimentation of suspended matter in sewage is susceptible to much less accurate mathematical analysis, for the reason that the particles of suspended matter are constantly changing in shape and hydraulic value, as a result of bacteriological and chemical changes which are continually taking place. The ebullition of gas is another factor which may exert a material influence upon the process. A considerable fraction of

the suspended matter in sewage is in a state of very fine (colloidal) division and cannot be removed by sedimentation.

The path described by the settling solids results from the action of a combination of forces, some known and some unknown. Any particle in moving sewage is traveling in a horizontal direction due to the velocity of the sewage, and also downward with a certain velocity, usually assumed as following Stoke's Law. Theoretically the resultant between these velocities should strike the bottom before the particle reaches the overflow weir and consequently the shallower the tank the more efficient.

In any theoretical discussion of the rate of settling of sewage particles, a number of variables appear, the most important being:

1. Period of retention
2. Depth of flow
3. Length of flow
4. Particle size
5. Electrical effects
6. Specific gravity of particles
7. Viscosity of liquid
8. Concentration of particles

## Mathematical Considerations

If the resistance, $R$, that a sphere encounters in falling through a viscous liquid is a function of the diameter, $D$, the viscosity, $\mu$, the density, $\delta$, and the velocity, $V$, then:

$$R = (f)\mu,\ V,\ \delta,\ D; \tag{1}$$

or, writing dimensionally

$$\frac{M}{LT^2} = \left(\frac{M}{LT}\right)^a \left[\frac{L}{T}\right]^b \left[\frac{M}{L^3}\right]^c \left[L\right]^d \tag{2}$$

solving for exponents in terms of $b$,

$$R = K\mu^{2-b}V^b P^{b-1}D^{-2+b} \tag{3}$$

$$= K\frac{\mu^2}{\delta D^2}\left(\frac{V\delta D}{\mu}\right)^b \tag{4}$$

or generalizing to include all values of $b$,

$$R = \frac{\mu^2}{\delta D^2}(f)\left(\frac{V\delta D}{\mu}\right) \tag{5}$$

$(V\delta D/\mu)$ is Reynold's number and $P\delta D^2/\mu^2$ is also a dimensionless number. If $\mu/\delta = \forall$ = kinematic viscosity,

$$\frac{R}{V^2\delta D^2} = (f)\frac{VD}{\forall} \tag{6}$$

For slow motion, the force is known to be $3\pi\mu DV$ (Stokes) *i.e.*, it is proportional to the velocity; for high speeds, the right hand quantity tends ultimately to be a constant and then $R$ is proportional to $V^2$.

In sewage sedimentation problems, the value of $VD/\forall$ does not reach the critical Reynolds number and the motion is of the slow type. When terms of the second order arise, they must depend on $V^2D\delta/\mu$ and bear the ratio to $V$ of $VD/\forall$ (Reynolds number). In the case of water, with $\mu/\delta = .01$ C.G.S. units, and in order that the ratio may be one-tenth, it follows that $VD$ should not be more than .001.

No satisfactory mathematical law has ever been derived for the relation between the dimensionless numbers $R/V^2\delta D^2$ and $VD/\forall$, which is applicable throughout the range of velocities, but Stoke's Law seems to fit the case for low velocities and for sewage sedimentation can be used with a maximum error of 5 per cent.

In the design of a sedimentation basin we are interested in building a model similar both dynamically and geometrically, so that the per cent removal of settling solids in the model and in the prototype will be the same. It is an easy problem to make the basins geometrically similar by making all linear dimensions equal to the corresponding dimensions in the homologue, divided by the scale ratio. Dynamic similarity requires that all pairs of homologous forces shall be in a fixed ratio. In case of gravity acting upon both model and prototype at the same place or locality, we know that other forces are proportional to the masses upon which they act so that for hydraulic models generally, as a necessary condition of geometric and dynamic similarity, we must have

$$\frac{V^2}{V_m^2} = \frac{r}{r_m} = \text{the scale ratio} \tag{7}$$

and

$$\frac{VD}{\forall} = \frac{\forall_m}{V_m D_m} \qquad \text{and} \qquad \frac{R}{V^2\delta D^2} = \frac{R_m}{V_m^2\delta_m D_m^2}$$

must be the same for all sections of the basin, including both inlet and outlet arrangements. In other words, one of the conditions of similiarity is that the resistances vary as their scale ratios.

## Use of Models

When models of sedimentation basins are tested to predict the performance of the full sized prototype, it is easy to construct them geometrically similar. The velocity of flow in the full sized basin should be $\sqrt{n}$ (square root of scale ratio) times the velocity in the model. If the model is geometrically similar the same relation holds true for the detention period. It is generally practicable to test the models at the place where the full sized structure will be built, hence the effect of

acceleration of gravity can be eliminated and the same sewage used as in the full sized prototype. If the proper corrections are made for temperature, it is reasonable to assume that the per cent removal of suspended solids in the prototype will be approximately the same as in the model.

It is unsatisfactory to test models for sewage settling basins on sewage different from that to be received at the full-size plant, on account of the variables which cannot be expressed mathematically, the most important of which is the colloidal factor. When the model is tested at the same location, with sewage of the same character as that to be received at the plant, it is possible to predict the performance of full-size basins.

Dynamic similarity must always be obtained in designing the inlet and outlet arrangements. The writer is familiar with one installation where a circular basin was tested and a large basin built with geometrically similar dimensions. The inlet was a submerged orifice at the bottom of a sloping sector. The loss of head in the full-size basin was so low that it was necessary to block off about 50 per cent of the openings to get fair distribution.

The increase in rate of sedimentation with increased concentration may be partially explained by the theory of probability. The probability of an event is the ratio of the number of favorable chances of its occurrence to the total number of chances, favorable and unfavorable.

Let it be assumed that a perfect sphere of known specific gravity and volume will settle through water at a definite velocity $V_1$. It will, also, be assumed that if the volume of the sphere is changed, the velocity will vary as the square of the diameter, according to Stoke's Law. It is also assumed that when two settling particles come together, they will form one particle whose volume is the volume of the two particles. Then if the two particles are of the same size and $V_1$ represents the velocity of sedimentation of one particle and $V_2$ of the two particles combined, by doubling the volume of the sphere the ratio of the diameter is

$$d_2 = \sqrt[3]{2}\, d_1$$

and, since the velocities vary as the square of the diameters,

$$V_1 : V_2 : : {d_1}^2 : {d_2}^2$$

$$V_2 = V_1 \sqrt[3]{(2)^2}$$

and the velocity of sedimentation of "$n$" particles of the same size after combining will be

$$V_n = V_1 \sqrt[3]{n^2}$$

As the combination of settling particles will increase the velocity of sedimentation, then the greater the number of particles the greater the probability of increase in rate of sedimentation.

If $N$ represents the number of particles in the liquid, the chances of increasing the velocity of sedimentation are:

$$\frac{N}{2} = 2^{2/3}; \qquad N/3 = 3^{2/3}; \qquad \frac{N}{m} = m^{2/3}$$

where "$m$" is the number of chances of the particles coming together. Some of the particles might have their velocities increased by $2^{2/3}$, some by $3^{2/3}$ and some by $m^{2/3}$, etc. And these might come together and form new particles so that the theoretical final velocity would be that of one, a single particle with a velocity of $V_n = V_1 N^{2/3}$. Figure 2 shows this

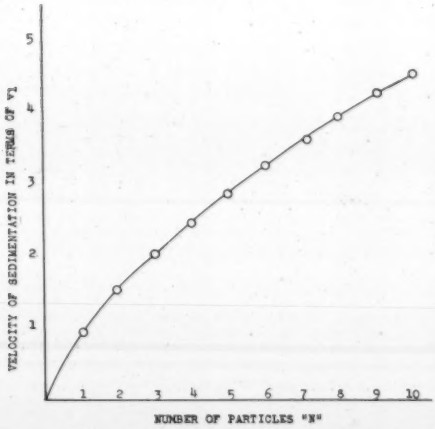


FIG. 2.—Theoretical relation number of particles and velocity.

Equation $V_n = V_1 N^{2/3}$.

graphically. It is assumed that all factors are constant, except the number of particles and the velocity of sedimentation. The graph shows that when the concentration is increased eight times the velocity is four times as great.

From the above reasoning it is possible to plot a theoretical percentage reduction curve. This curve would really be the reciprocal of the velocity curve. If $P_1$ represents the per cent removal with $N_1$ particles present and $P_2$ represents the per cent removal with $N_2$ particles present, and if $N_2 = mN_1$

$$P_2 = m^{2/3} P_1$$

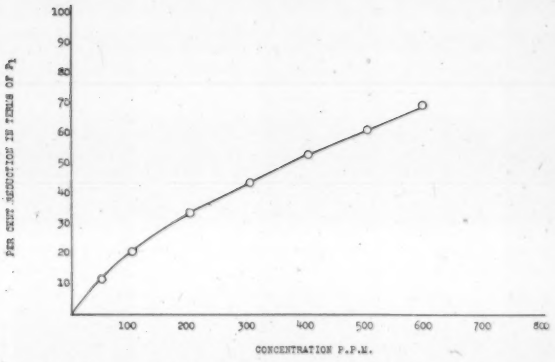


FIG. 3.—Theoretical relation between per cent reduction and concentration.

Equation $P_2 = m^{2.3}P_1$.

Figure 3 shows this relation graphically. This represents the theoretically ideal curve of probability below which all actual observations should fall.

## EFFECTS OF TEMPERATURE

Practically all sedimentation basins show greater removal of solids in summer than in winter. This is the result of the change in viscosity of the water. The relation between the temperature and the per cent removal of suspended solids is given by the empirical formula developed by the writer at the University of Illinois:

$$R = \frac{40}{50 - t}$$

where $t$ = temperature in degrees Centigrade. A particle of certain specific gravity would settle twice as rapidly at 25° as it would at 10° Centigrade.

## FLOWING-THROUGH PERIOD

The flowing-through period is defined as "the average time required for a small unit volume of liquid to pass through a basin at a given rate of flow." The efficiency of a basin is calculated as the flowing-through period divided by the time for volumetric displacement of the fluid. It is difficult to determine the actual flowing-through period by ordinary methods. The most common method is that of adding salt in known concentration to the inlet and collecting samples at the outlet. The

efficiency is then determined by plotting the chloride titrations of the effluent against time. The center of gravity of the area between the two curves is determined by the method of moments, and the time corresponding to this point is called the flowing-through period.

In some experimental work at Morgantown a set-up such as that shown in Fig. 4 was used. A pair of electrodes, one of zinc and the other

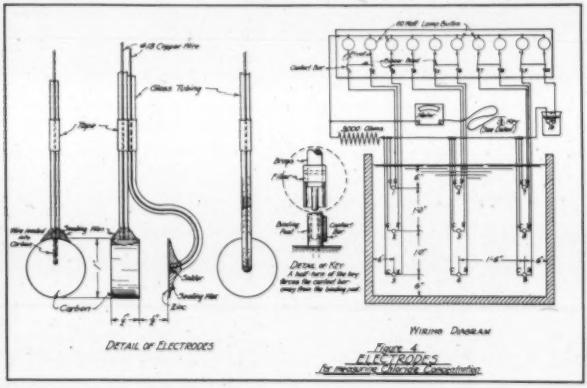


Fig. 4.

of carbon, was immersed in the salt solution and connected in series with suitable resistance and a micro-ammeter, the voltage being produced by the unlike metals in solution. The device was found to be extremely sensitive, especially in solutions of low salt concentration. These electrodes were designed to trace the distribution of currents over the cross-section of a basin, but the results were not satisfactory except in perfectly clear water, as sediment had a tendency to accumulate on the electrodes and render them unreliable. In all experimental work the efficiency was calculated from the removal of suspended solids by the weighing of the filtrate in a Gooch crucible according to Standard Methods of Water Analysis.

## Sedimentation Formula

Holmes[6] has suggested the use of the following formula which fits the experimental data from Rochester:

$$E = AS - S(A - 1)e^{-kt^m} \qquad (1)$$

$$= S\left[A + \frac{(1 - A)}{e^{kt^m}}\right] \qquad (2)$$

$E$ = p.p.m. suspended solids in effluent,
$t$ = time of detention,
$S$ = p.p.m. suspended solids in influent,
$A$, $k$, $n$ are constants.

This equation is rational because $E$ equals $S$ when $t$ is 0 and when $t$ approaches infinity $E$ is a definite value, based on the strength of the sewage.

For a crude sewage of 150 p.p.m.,

$$A = 0.25; \quad K = 0.378 \quad \text{and} \quad n = 0.3145$$

$$E = 37.5 + \frac{112.5}{e^{.378t.3145}} \tag{3}$$

Table I shows a comparison between the results for various periods

TABLE I

| $t$ Detention Period | $E$ Suspended Solids in Effluent from Formula | $E$ Suspended Solids, Rochester Experiments | $E$ Suspended Solids W V U. Experiments |
|---|---|---|---|
| 5 | 97.6 | 110 | — |
| 10 | 88.5 | 94 | — |
| 15 | 83.5 | 87 | 95 |
| 20 | 80.1 | 80 | 88 |
| 30 | 74.9 | 75 | 78 |
| 45 | 69.6 | 70 | 72 |
| 60 | 66.2 | 66 | 68 |
| 90 | 61.3 | 61 | 61 |
| 120 | 58.0 | 59 | 60 |
| 240 | 51.0 | 51 | 50 |

Table I is based on:

$$E = AS - S(A - 1)e^{-kt^n}$$

where
$A = 0.25$
$K = 0.378$
$n = 0.3145$
$A = 150$ p.p.m.

of detention using equation (3) and actual experimental results. The values of $A$, $K$, and $n$ will vary with the concentration of suspended solids in the influent. Sufficient data are not available to correlate each of these constants for all concentrations, but results at Syracuse indicate that this formula is applicable to sewages with from 150 to 500 p.p.m. suspended solids, as determined by the Gooch crucible method.

Another formula which fits a large amount of data is:

$$E = \frac{1.53S^{0.75}}{t^{0.94}S^{0.125}} \tag{4}$$

using the same nomenclature as in formula (1). This formula is not rational. Fig. 5 gives experimental results at Syracuse.

Babbitt [6] presents a rather lengthy formula for calculating the per cent removal of settling solids with various periods of detention and various concentrations of settling solids in the influent. Unfortunately,

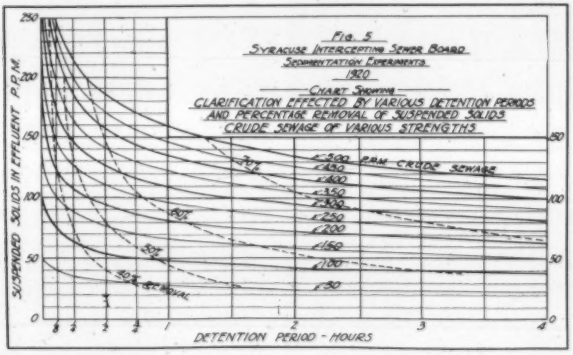


FIG. 5.

this formula is based on the removal of settling solids by a special non-standard method and the results are not comparable with data from other sources.

## SUMMARY

Two formulas (1) and (4), based on experimental results, are presented which are satisfactory for estimating the probable performance of a sedimentation basin.

The principles of similarity are discussed with respect to the use of small basins for predicting the performance of larger basins.

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## Discussion

### "Notes on Sedimentation"

**Francis C. Foote,** *Morris Knowles, Incorporated Engineers, Pittsburgh, Pennsylvania:* It is perhaps well to emphasize the fact borne out by Professor Carpenter that there are so many variables entering into the problem of sedimentation, with respect to sewage, that we cannot be guided entirely by mathematical equations. With water, however, containing largely sand and silt, more reliable mathematical analyses can be made. The fundamental equations are, of course, those presented by Hazen and Stokes, the latter one being well known as "Stokes Law."

I believe that we can well afford to give more attention to the use of models in the design of sedimentation basins, bearing in mind the precautions to be followed in the conversion of dimensions and velocity from the model to the final structure. Likewise, in the arrangement of inflow and outflow facilities, due to different hydraulic conditions, it is not always practical to obtain results with models that will be comparable to those of the actual structures when completed. Obviously, as Professor Carpenter has pointed out, experimental data of this sort can be secured only at the location where the tanks are to be constructed.

Even after giving due consideration to the various factors involved in the theoretical design of a sedimentation basin, we are prone to disregard some of our theoretical discussions when we come to actual construction. This is not always due to any real contempt for theories, but for reasons of economy in design and simplicity or ease of construction. We give serious thought to the period of retention when designing a basin and yet when the structure is completed and tests conducted, the actual flowing-through period may be anywhere from 10 to 50 per cent of the theoretical period of retention for the particular basin in question. If properly proportioned to reduce eddies around the inlet, a basin which gradually diverges from its inlet to its outlet would give ranges in velocity suitable to take care of particles of various sizes and specific gravity. Because of their shape, however, basins of this type are not economical in that too much land area is required. Likewise, although considerable stress has been laid upon the proper theoretical design of inlets and outlets to secure uniform distribution of flow, it is difficult to obtain the desired effects in actual practice.

Perhaps the real difficulty in obtaining the desired results in practice is that by far the greater number of sewage treatment plants constructed today are those of small or medium sized capacities. In the case of large plants, many units can be constructed to take care of varying conditions in flow, so that each unit is utilized to the best advantage. In the case of smaller plants, these must of necessity be designed to

provide for a reasonable increase in quantity, and often from the point of view of economy it is not possible to provide a sufficient number of units to secure uniform operation of the individual basins, with the variation in rates of flow of sewage throughout the day.

It is of interest to note that more consideration is being given today to the question of proper baffling in sedimentation basins. The experiments conducted by Morrill at Detroit, and more recently at Chicago and Aurora, Illinois, show that increased efficiency may be obtained with the proper use of baffles. It is perhaps worth our while to give more attention to this feature.

To those interested in the question of design, it will prove beneficial if the operators of sewage plants will make it a point to collect actual performance data which can be made available to those desiring to make further studies on this important question of sedimentation. In this connection, I am wondering if Professor Carpenter has secured any data on the effect of mechanical equipment for the removal of sludge in sedimentation basins, with particular regard for the effect produced by different velocities of travel of the collecting apparatus.

**Mr. F. B. Milligan,** *Emporium:* You referred to proper baffling as improving the effectiveness of the settling tank. Will you give an explanation of what you mean by "proper baffling"?

**Mr. Foote,** *Pittsburgh:* By proper baffling we mean baffling which will give the greatest value for basin capacity by avoiding eddies and getting the maximum flowing-through period. In some cases consideration has been given to longitudinal baffles.

**Mr. Milligan:** Do you have any definite principles other than those you have mentioned for the design and placing of the baffles? Given a tank of certain average dimensions, the old way apparently was to use over-and-under flow baffles, placed transversely, perhaps at quarter points. Have you any basis for design—any particular principle—to go by? Would you put dye in your tank and try to solve the problem of baffling by experiment, either after the tank was built, or beforehand with a model?

**Mr. Foote:** Both methods could be used.

**Mr. Milligan:** Have you ever seen a tank wherein the designer used baffles with vertical openings closed by removable slats? The baffled tank then could be built and put into service, and some of the salts knocked off or shortened afterward in order to adjust the flow.

**Mr. Foote:** That is what Morrill did at Detroit.

**Mr. H. M. Freeburn,** *Philadelphia:* There may be a number of operators who think this is another fad, and they may wonder how it affects them. The more you study the sedimentation question, I think, the less you feel you know about it. There is a real need for scientific work

along this line and this is one way it can affect you. If a designing engineer constructs a basin which is supposed to have a certain retention period and it hasn't, it means that solids are going to go out of that tank and clog up the oxidation or secondary treatment units.

I think there is too much tendency for designers to assume that they are absolutely correct in their design of baffles. They design a plant and put in concrete baffles which can't be moved. I have held the opinion for some time that baffles should be adjustable in all directions—so that they could be put in and tried to see what they will do. If they don't work, move them up or down, forward or back until you get the best conditions with your particular tank.

**Mr. R. O'Donnell,** *State College:* I believe that Professor Carpenter emphasized the point made by Mr. Freeburn, that model study in the future is going to be one of the guiding principles in design; that the designing engineer will resort more to the use of models in a specific locality with the specific sewage that is to be treated, and base them not only upon dimensional similarity but upon dynamic similarity also.

**Mr. H. N. Lendall,** *New Brunswick, N. J.:* You may be interested to know of some experiments we have carried on for over a year. Starting with sedimentation and realizing in the beginning the importance of velocity distribution throughout the tank, we made different shaped tanks with different inlet and outlet conditions. We divided the model tank into sections and had in each of those sections a series of threads. We had a model tank, of course, and we divided that tank into about six sections with about eight threads across the tank in each section. Varying the rate of discharge through the tank, getting an idea of the relative velocities, and measuring the inclination of each thread at various points throughout the tank in each section, gave a very excellent picture of the velocity distribution throughout the tank. We have used the baffles in various positions and as far as we have gone it has been demonstrated that we get the best flow conditions, in other words, we get a more nearly uniform flow throughout the full length of the tank and across the tank, when we have baffles placed a short distance from the inlet and from the outlet and at a depth of approximately one-fourth of the depth of the model tank. That has worked out for two kinds of tanks with different inlet conditions. As to whether we can apply that to a floating type, full-size tank, has yet to be investigated and learned.

**Mr. F. W. Jones,** *Cleveland:* Do you refer to a solid bafflle?

**Mr. Lendall:** Yes—solid.

**Mr. H. J. Krumm,** *Allentown:* At our water filtration plant, our settling tank instead of providing a retention period of three hours, gives only a one or one and a half hour retention period. We pre-chlorinated and then took samples at depths of two or three feet for residual chlorine,

and in that way found where the baffles should be. The problem now is to get the proper kind of baffle.

**Mr. R. L. Phillips,** *Meadville:* We are rather proud of the settling results we are getting at Meadville.

**Mr. H. N. Herr,** *Hershey:* In our secondary sedimentation basins at Hershey I provided triangular wedges at the inlet end of the basin. There are four notches and I installed a triangular wedge for each notch, also vertical holes in the basin. Those holes can be either opened or closed and the triangular wedges can cut down the amount of flow that goes through any one of these openings or they can direct the flow in a certain direction going through the openings. Through experimentation with dyes we succeeded in getting a fairly good distribution.

# BIOCHEMICAL CHANGES IN THE FORMATION OF ACTIVATED SLUDGE*

By H. Heukelekian

*Associate, Dept. Water and Sewage Research, New Brunswick, N. J.*

In a previous publication[1] data were presented concerning the changes in the suspended solids content and B.O.D. caused by the aeration of sewage, sewage and sludge mixtures and of activated sludge alone. No reference was made to the effect of the accumulation of activated sludge. It seemed to us that the characteristic changes noted during the above studies could best be followed by the production of activated sludge from raw sewage. The results reported herewith are therefore concerned with the simultaneous changes taking place in the liquor and the sludge produced from sewage during continuous aeration. If the properties of the activated sludge could be determined by the indices we have used, there should be a definite change in the value of these indices starting with sewage and continuing with the accumulation of sludge. The effect of aeration after sludge has been produced should also be reflected in these measurements.

## Method

Sewage from Plainfield was concentrated by filling a barrel, allowing it to settle for one-half hour, decanting the supernatant liquor, refilling and resettling. One hundred liters of sewage concentrated in this manner was aerated continuously for a period of 20 days in a tank 26 by 10 inches in plan and 10 inches deep, by means of a diffuser tube in the bottom of the tank. At intervals, 10 liters of sample was withdrawn, settled in a carboy for 1 hour, the supernatant withdrawn and the solids resettled in a cylinder for one-half hour. The following tests were made on the withdrawn liquor: suspended solids, ash in suspended solids, nitrate nitrogen, dissolved oxygen, B.O.D. and pH. The sludge volume was determined after one and one-half hours of sedimentation. The sludge was analyzed for suspended solids and ash, total solids and ash, and B.O.D. A part of this sludge, used as returned sludge, was mixed with raw sewage and the purifying power of the sludge determined by the difference in the suspended solids and B.O.D. of the raw sewage and of the supernatant liquor after six hours of aeration and one-half hour of sedimentation.

* Journal Series Paper, N. J. Agricultural Experiment Station, New Brunswick, N. J., Dept. Water and Sewage Research.

## Results

The changes in the solids and ash content are given in Table I. The changes in the mixture and in the settled sludge are considered separately. It will be seen that there was a large content of suspended solids in the original sewage. The sewage was concentrated, as described above, so that appreciable amounts of sludge could be obtained for making the various tests considered desirable. The reduction of suspended solids in the mixture was rapid during the first seven days of aeration. We have reported elsewhere [1] approximately 15 per cent reduction of suspended solids in 48 hours by the aeration of sewage. The reduction of suspended solids continued with longer aeration periods, but at a decreasing rate. Simultaneous with the loss of suspended solids a loss of ash in the suspended solids was also taking place, so that the percentage of ash in the suspended solids did not increase during the first seven days of aeration. In the previous study [1] the per

Table I.—*Changes in the Solids Content in the Production of Activated Sludge by Continuous Aeration of Sewage*

| | Days Sewage Aerated | | | | |
|---|---|---|---|---|---|
| | 0 | 4 | 7 | 12 | 20 |
| Suspended Solids in Mixture, P.P.M. | 875 | 675 | 490 | 460 | 530 |
| Reduction of Suspended Solids in Mixture, Per Cent | 0 | 22.8 | 44.0 | 47.2 | 39.6 |
| Ash of Suspended Solids in Mixture, P.P.M. | 160 | 125 | 80 | 100 | 165 |
| Ash of Suspended Solids in Mixture, Per Cent | 18 | 18.6 | 16.3 | 22.1 | 31.0 |
| Suspended Solids Concentration in Sludge, P.P.M. | 21,430 | 16,890 | 14,585 | 11,380 | 11,185 |
| Quantity of Suspended Solids in Sludge from 1 Liter of Sewage, P.P.M. | 645 | 565 | 510 | 450 | 470 |
| Reduction of Total Suspended Solids in Sludge Produced from Sewage, Per Cent | 0 | 12.3 | 20.7 | 30.2 | 27.0 |
| Suspended Solids in Mixt.,—Susp. Solids in Sludge per Liter Sewage, P.P.M. | 230 | 110 | −20 | 10 | 60 |
| Ash in Suspended Solids of Sludge, P.P.M. | 107 | 130 | 135 | 133 | 151 |
| Ash in Suspended Solids of Sludge, Per Cent | 16.6 | 23.0 | 26.5 | 30.0 | 32.1 |
| Volume of Sludge After 1½ Hr. Sedimentation, Per Cent* | 1.9 | 3.3 | 3.1 | 3.6 | 4.0 |
| Sludge Index $\frac{\text{(Volume in Per Cent After 1½ Hr. Sed.)}}{\text{S.S. in Sludge in Per Cent}}$ | 30 | 60 | 60 | 80 | 85 |

* The volume of sludge actually obtained after decanting the supernatant liquor was higher than values given here.

cent of ash in the suspended solids of sewage did not show a material increase during 48 hours of aeration. When the maximum reduction in the suspended solids had taken place (seven days) then not only the relative percentage of ash increased but also the absolute quantity. In the early stage of oxidation the loss of suspended solids and ash kept pace, while in the later stage the loss of suspended solids ceased and the ash content increased, resulting in an increase of the percentage of ash in the solids.

The concentration of the sludge separated from the sewage decreased with the length of aeration period. The volume of the sludge formed from the sewage was increasnig, due to building up of sludge. Therefore, the actual quantity of suspended solids in the sludge separated from one liter of sewage was obtained by multiplying the suspended solids concentration of the sludge by the volume of the sludge obtained. These values indicate a progressive decrease of the suspended solids of the sludge. The percentage decrease of the suspended solids of the sludge was less than the percentage reduction of the suspended solids of the whole mixture. When the amount of suspended solids in the sludge from one liter of the mixture was subtracted from the suspended solids of the whole mixture the results represented the amount of suspended solids in the mixture that did not form sludge, *i.e.*, the dispersed non-settleable suspended solids. These values were high initially and as the aeration progressed the values became smaller until the seventh day when a negative value was obtained. At this time all the suspended solids were in the form of settleable sludge. With further aeration the amount of non-settleable dispersed solids again increased. The ash of the suspended solids in the sludge produced from one liter of sewage increased, in contrast with the decrease in the ash content of the suspended solids of the whole mixture. Since the decrease in the suspended solids content of the sludge was greater proportionately than the decrease in ash, the percentage ash in the sludge suspended solids steadily increased. The sludge index of the sludge from the raw sewage was low and increased with aeration.

The B.O.D. changes during the aeration of sewage and production of activated sludge are given in Table II. The B.O.D. of the sewage decreased with aeration, the maximum reduction taking place during the first four days of aeration. In the studies reported previously[1] a 52 per cent reduction of the B.O.D. of sewage took place during 48 hours of aeration. In the present study a 54 per cent reduction was obtained in four days. The B.O.D. reduction of the sludge itself was lower than that of the whole mixture. The difference between the B.O.D. of the mixture and that of the sludge, representing the B.O.D. of the supernatant, was high initially and steadily decreased with the aeration

TABLE II.—*B.O.D. Changes in the Production of Activated Sludge by the Continuous Aeration of Sewage*

| | Days Sewage Aerated | | | | |
|---|---|---|---|---|---|
| | 0 | 4 | 7 | 12 | 20 |
| B.O.D. of the Mixture, P.P.M. | 765 | 350 | 210 | 180 | 100 |
| B.O.D. Reduction of the Mixture, Per Cent | 0 | 54.2 | 72 | 76.5 | 87.0 |
| B.O.D. of the Sludge from 1 Liter Sewage, P.P.M. | 305 | 235 | 120 | 100 | 50 |
| B.O.D. Reduction of the Sludge, Per Cent | 0 | 24.1 | 61.1 | 68.0 | 84.3 |
| B.O.D. of the Mixture—B.O.D. of the Sludge, P.P.M. | 460 | 115 | 90 | 80 | 50 |
| Reduction of the Dispersed Material, Per Cent | 0 | 75 | 80 | 82 | 83 |
| B.O.D. of Sludge / Suspended Solids in Sludge | .47 | .41 | .23 | .22 | .11 |
| B.O.D. of Mixture / Suspended Solids in Mixture | .87 | .52 | .43 | .40 | .19 |

period. The oxidation of this dispersed supernatant material, as measured by the per cent reduction of B.O.D., was the most rapid, followed by the oxidation of the whole mixture containing both the supernatant and the sludge and finally the oxidation of the sludge portion. Ratio of B.O.D. to suspended solids of the sludge portion started at 0.47, reaching a value of 0.23 and 0.11 in 7 and 20 days respectively. The B.O.D. to suspended solids ratio of the mixtures showed a similar tendency, except that the initial and subsequent values were higher. In the previous studies these ratios in the raw sewage were reported as 1.0 and for sewage aerated for 48 hours, 0.67. In the present sludge the ratio for raw sewage was 0.87 which decreased to 0.52 after 4 days of aeration.

The nitrate formation, pH values and dissolved oxygen content of the aerated sewage are given in Table III. It will be seen that appre-

TABLE III.—*Effect of Aeration on Nitrate and Dissolved Oxygen Content and pH Value of Sewage*

| | Days Sewage Aerated | | | | |
|---|---|---|---|---|---|
| | 0 | 4 | 7 | 12 | 20 |
| Nitrate N, P.P.M. | 0.4 | 0.6 | 9.0 | 22.0 | 20 |
| pH Value | 7.1 | 7.6 | 7.9 | 7.6 | 7.8 |
| Dissolved Oxygen, P.P.M. | 0 | 5.1 | 5.7 | 6.2 | — |

ciable quantities of nitrates were formed only after seven days of aeration, the concentration increased further after twelve days of aeration. The pH value increased with aeration. Dissolved oxygen appeared in the sewage after four days and increased gradually up to twelve days.

In Table IV are given results with the sludge produced after different periods of aeration, when mixed with sewage and aerated for six

TABLE IV.—*Purifying Power of the Activated Sludge Produced During the Continuous Aeration of Sewage (Aeration Period, 6 Hrs.)*

| | Days Sewage Aerated | | | |
|---|---|---|---|---|
| | 0 | 4 | 7 | 12 |
| Suspended Solids of the Mixture, P.P.M. | 1775 | 2265 | 1945 | 2020 |
| Suspended Solids of Influent, P.P.M. | 450 | 410 | 340 | 515 |
| " " " Effluent, P.P.M. | 120 | 165 | 60 | 210 |
| " " Reduction, Per Cent | 73 | 60 | 82 | 60 |
| B.O.D. Influent, P.P.M. | 530 | 525 | 345 | 500 |
| B.O.D. Effluent, P.P.M. | 170 | 75 | 105 | 285 |
| B.O.D. Reduction, Per Cent | 68 | 85.7 | 70 | 43 |

hours. This should represent the effect of the different stages of oxidation of the sludge on the degree of purification brought about by it. The object was to make the conditions of the different mixtures in regard to suspended solids concentration, period and rate of aeration as nearly the same as possible; the only variable being the degree of oxidation of the sludge. The suspended solids of the mixtures made with activated sludge at different periods showed a maximum variation from 1776–2265 p.p.m. The sewage used for the mixture at different periods was possibly the only variable factor that could not be controlled, although its strength as measured by suspended solids concentration and the B.O.D. did not vary excessively. The purification, as measured by suspended solids and B.O.D. reductions, was high with the sludge obtained initially from sewage, so that the results obtained with sludge after different periods of aeration did not show appreciably greater improvement. As measured by suspended solids reduction the sludge was at a maximum efficiency after seven days of aeration, while accordnig to the B.O.D. reductions the same point was reached after four days of aeration. According to both suspended solids and B.O.D. reductions the efficiency after twelve days of aeration was lower than with the sludge obtained from the original sewage.

## Discussion

It has been shown that in the aeration of sewage there is a definite and appreciable reduction of suspended solids and B.O.D. These reductions are the result of actual oxidation by air and not due to the flocculation and removal after aeration and settling. The total reduction due to settling after aeration will be considerably higher than the values recorded here. During aeration an increasing proportion of the suspended solids in the sewage is being transferred into the sludge, giving rise to an increased volume of sludge, up to a point where all the suspended solids in the aerated sewage can be recovered in the sludge. Aeration beyond this point causes a dispersion of the sludge floc.

The oxidation of the dispersed material proceeds at the highest rate and the oxidation of the flocculated material at a slower rate, while oxidation of the mixture made up of these components takes place at an intermediate rate. The oxidation of the sludge floc after it is formed plays an important role in the properties of the sludge. Measuring the property of the sludge by its purifying power shows that the optimum stage of oxidation was attained between four and seven days. The initial unaerated sludge yielded a surprisingly high degree of purification and the purification caused by an over aerated sludge (twelve days), was lower than with unaerated sludge. It will be of interest to note that the re-dispersion of the sludge floc coincided with the poor efficiency of the sludge when returned to the sewage. Oxidation as measured by nitrification would also place the optimum stage of the oxidation on the seventh day. An excessive amount of nitrate accumulation on the twelfth day was probably another indication of over-oxidized sludge. According to these different criteria the sludge at its optimum stage of oxidation had an ash content of about 25 per cent. According to the B.O.D. to suspended solids ratio of the sludge, the optimum stage of oxidation again was attained between the fourth and seventh days, since between these two periods the ratio decreased from 0.41 to 0.23. From previous studies we had arrived at a value of 0.3 for a well oxidized sludge.

It will be observed that the ash content of the sewage decreased during aeration, while that of the sludge separated from it increased. This phenomenon of loss of ash under certain conditions of aeration and digestion has been observed before. It is logical to assume that these apparent losses of ash are due in part to some error in drying and ignition. It seemed possible that one of the factors involved was the loss of bicarbonates during drying and ignition. Accordingly, on a sample of sewage total solids and ash determinations were made in the usual manner. Carbonates were run on the wet, dry and ignited sam-

ples by aspirating $CO_2$ free air through the heated and acidified sample and catching the $CO_2$ in $Ba(OH)_2$. The results of such an experiment on the original sewage and on the same sewage after three days with and without aeration are given in Table V. It will be seen that considerable amounts of carbonates are lost on drying and igniting a sewage sample.

TABLE V.—*Loss of Carbonates on Drying and Ignition*

| | Initial, P.P.M. | After 3 Days | |
|---|---|---|---|
| | | No Air, P.P.M. | Air, P.P.M. |
| Total Solids | 1090 | 1080 | 855 |
| Ash | 480 | 440 | 420 |
| Carbonates in Wet, as $CO_2$ | 175 | 225 | 160 |
| " " Dry, " " | 30 | 55 | 55 |
| " " Ash, " " | 10 | 10 | 5 |
| Error in Total Solids Due to Loss of Carbonates, Per Cent | 12 | 13 | 11 |
| Ash plus Carbonates Lost in Ignition | 645 | 655 | 575 |
| Error in Ash Due to Loss of Carbonates, Per Cent | 26 | 33 | 27 |

The errors introduced into the total solids and ash determinations through this source are considerable. When the actual loss of carbonates on ashing are added to the ash, the loss of ash in unaerated sewage is compensated but the aerated sewage still gives lower ash figures than the initial. The loss of some other material in the ash during aeration is probably responsible for this discrepancy. It is interesting to note in this connection that the ash content of the sludge did not show a decrease. Since the carbonates are lower in the sludge than in the liquid portion, this was to be expected.

## SUMMARY

The biochemical changes involved in the aeration of sewage and production of activated sludge were studied. The two main processes involved are flocculation and oxidation. Aeration enhances flocculation by transferring the sewage solids into the sludge floc. Over-aeration causes a re-dispersion of the flocculated solids. Simultaneous with the flocculation, oxidation of the solids in the dispersed as well as in the floccular form is taking place, the former at a more rapid rate than the latter. The completion of the most rapid rate of oxidation, as measured by the reduction of suspended solids and B.O.D., coincided with the

maximum purifying efficiency of the activated sludge. After four to seven days of aeration an over-oxidized condition was created, as measured by re-dispersion of the sludge floc, decreased purifying efficiency and an excessive amount of nitrate accumulation. The optimum stage of oxidation as measured by the B.O.D. suspended solids ratio of the sludge was also attained between four and seven days. The percentage of ash in the sludge increased from 16 to 26 per cent after seven days of aeration, while the absolute amount of ash in the mixture decreased. It has been shown that carbonates are lost on drying and ignition. As the carbonates increase during aeration this would cause an apparent decrease of ash.

## References

1. H. Heukelekian. "Effect of Aeration on the Rate of Oxidation of Activated Sludge." This Journal, 6, 897–907 (1934).

# Plant Operation

## SEWAGE TREATMENT PROBLEMS AND TRENDS*

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### The Changing Character of Municipal Sewage

The success of treatment plants and disposal processes must be measured by their ability to handle, with that degree of efficiency for which they have been designed, all volumes and conditions of sewage likely to be received by them. In the design of such works the engineer must consider any changes likely to take place with respect to the character and composition of the sewage, as well as its quantity.

Certain changes in the character of our American municipal sewages have been taking place due to the changing food habits of our people, to changing processes of manufacture and procedure of disposal of industrial wastes, and, in general, to changing economic and social conditions.

With the decreased cost of soap and the increased use of hot water in homes, grease which was formerly salvaged for soap making or was sent to the garbage can is now washed down the kitchen sink. There is undoubtedly an increasing general use of soap, soap powders and other household cleaning materials and these are doubtless responsible for an increase in the content of saponified fats in American sewages. Despite all ordinances and inspections to the contrary, mineral oils in large aggregate quantity find their way into the sewers from public and private garages, perhaps particularly from the latter. While the use of grease and oil traps in kitchens and garages, respectively, is increasing in some communities, these devices are too often grossly inadequate and ineffective.

The tendency in manufacturing communities is seemingly toward a greater diversity of product; therefore toward a greater diversity of industrial wastes. The chemical industry, in particular, is developing many new products, some of which create wastes of great significance from the treatment and disposal standpoint. Birmingham, England, boasts of 1,200 different trades or industries. There are probably few,

* Luncheon address given at the Seventh Annual Meeting of the New York State Sewage Works Association, held in New York City, January 15, 1935.

if any, American cities which can claim such diversity at the present time but the trend toward such diversity demands our attention.

In the canning industry wastes formerly removed in solid form from the plants are now reduced to a pulp in a hammer-mill or other type of disintegrator, are mixed with water and are flushed into the sewers. Even apricot and peach pits are thus disposed. Prior to this recent development and with a smaller proportion of the cannery wastes reaching the sewers, the loads placed upon sewage treatment plants by canneries were sometimes very great, both in absolute and relative terms. For example: in the town of Lodi, California, having a connected population of about 7,500 persons, the wastes from a single cannery during its peach "campaign," when some 45 to 50 tons of peaches were being processed daily, represented a B.O.D. load equivalent to that of the normal sewage contribution from at least 8,000 persons. This extra load doubled the equipment required to be in service at the city's activated sludge treatment plant. In Sacramento, a city of some 90,000 inhabitants, the wastes discharged into the sewers from three canning establishments, during the maximum months of their campaigns, had an average B.O.D. requirement estimated to be equivalent to the sewage contribution of some 66,000 persons. Such wastes are seasonal and in this particular instance were for the most part contributed during the months of June, July, August and September.

At the present moment the feasibility of disposing of garbage in the sewers, either directly from individual homes, markets, etc., or from central grinding stations, is being discussed and in some quarters actually advocated. If this contribution to the sewage could exist solely in the form of insoluble solids the effect as related to sewage treatment would not perhaps be very serious. Unfortunately, however, garbage is of such a nature that it will greatly increase the colloidal and dissolved organic matter. Such substances at best are difficult and expensive to treat and remove. Serious consideration should be given to the economics of the problem; possibly also to the esthetic implications, including odor production. The disposal of garbage by digestion in combination with sewage sludge is quite a different matter. Such disposal does not affect the entire volume of sewage flow requiring treatment.

The comminution of screenings, referred to hereinafter, within the treatment plant itself and return of the ground solids to the sewage behind the screens, to be removed by subsidence, may or may not add appreciably to the volume of scum and to the load of colloidal and dissolved organic matter in the sewage, depending upon the manner and extent to which comminution takes place.

Many of these changing conditions, particularly as related to oil and

grease, are not now and never have been reflected by routine chemical determinations. Moreover, our chemical laboratory determinations and methods have gradually undergone such a complete change that, except for solids—total, dissolved and suspended—there is rarely to be found in laboratory records any present day criterion of sewage character and composition which reaches far back into the past and thus affords a basis for comparisons.

### The Increasing Use of Mechanical Appliances

Throughout virtually the entire field of sewage treatment the continued development and use of mechanical appliances is to be noted. The increase in the number of patents involved is large and disconcerting. It is difficult to predict the outcome of this patent development. Under the circumstances, with valuable process and equipment patents held by a considerable number of manufacturers, scarcely any process or mechanism can have all of the good features which it should possess. In general, however, much of the available equipment is so excellent that designers of sewage treatment works are possibly too prone to accept some readily available mechanism rather than to attempt the more difficult enterprise of developing new devices.

In particular, perhaps, the development and recently increasing utilization of mechanical equipment in the sewage works field may be noted as follows:

(1) mechanically cleaned bar screens, even in comparatively small plants;
(2) mechanically cleaned grit chambers for storm and combined sewage;
(3) comminutors or disintegrators for bar screenings, returning these to the sewage behind the screens and in advance of sedimentation basins;
(4) mechanically cleaned sedimentation basins;
(5) rotary and reciprocating dosing mechanisms for trickling filters, following the practice developed and advanced in England many years ago but only recently introduced in the United States;
(6) vacuum, centrifugal and other types of dewatering equipment for raw and digested sludges;
(7) new and improved mechanical methods for drying sludges to powder form, with or without subsequent incineration.

While a considerable amount of experimentation has been recently conducted with reference to the mechanical agitation of sludge in digestion tanks, the evidence respecting the advantage of such agitation is not altogether convincing. There is assuredly a tendency to construct sludge digestion tanks without special means of agitation other than

circulation by the use of the plant sludge pumps themselves, and, in general, to question the practical and economic value of more elaborate agitating devices.

### Increasing Use of Screenings Disintegrators or Comminutors

The work of the Chicago Sanitary District at the North Side plant demonstrated that bar screenings could be successfully disintegrated and returned to the sewage, thus eliminating the necessity for separate collection and disposal of this material, which hitherto had usually represented a somewhat difficult problem. There is some danger of poor results if the screenings are so treated as to be difficult of subsidence and as to form scum.

During the past two years a number of devices for grinding screenings have been developed and installed. One of the latest of these combines the procedure of screening and of comminuting the separated material in a single mechanism.

More recently it has been proposed, where local conditions favor such a procedure, to deliver bar screenings direct to sludge digestion tanks, with or without disintegration. Such digestion tanks for small plants have recently been placed upon the market.

Engineers must recognize and properly provide for the additional load of settleable solids, and perhaps an increased volume of scum as well, in some cases, consequent upon the return of the disintegrated screenings to the sewage.

### Screenings Incineration

The disposal of the relatively large volume of screenings removed from sewage by the process of fine screening has also presented a difficult problem, and furthermore, one hitherto solved in most cases with but partial success. Screenings from fine screens have variously been disposed of with the mixed city refuse, or by burial in pits or trenches, by composting, and by partial dewatering and incineration. Designing and operating engineers have long been awaiting the development of a simple, effective and economical screenings incinerator.

By far the largest fine screen installation in America is at the Hyperion Plant of the City of Los Angeles, treating an average daily flow of 130 million gallons. For many years the screenings have been ejected to elevated sand dunes where they have been buried in trenches. During the past year works for the incineration of the screenings have been constructed and placed in successful operation. There is reason to believe that this pioneer development will be followed by others. Briefly, the main features of the plant are:

(1) an ejector tank providing sufficient storage to handle peak loads;
(2) a continuous roll press or so-called filtering machine for partially dewatering the screenings;
(3) a storage bin for the partially dewatered (70 ± % moisture) pressed screenings, located immediately over the furnace;
(4) a high-temperature oil-burning incinerator or furnace, with suitable chimney, for the destruction of the screenings;
(5) ash handling equipment;
(6) all necessary control and measuring apparatus;
(7) an industrial type of housing.

### Pre-treatment of Sewage to Remove Oil, Grease and Scum

The unwelcome occasional, if not persistent, appearance in recent years of large amounts of mineral oils in municipal sewages has been mentioned.

When sewage is disposed of by dilution, the presence of oil and grease manifests itself on the surface of the water as sleek, a rather definite index of marked sewage pollution.

The presence of mineral oils in aeration tanks of the activated sludge process has long been recognized, particularly in England, as a decided detriment. The high surface tension of oily sewage reduces the efficiency of aeration. Moreover, the presence of mineral oil in considerable quantities may have a toxic effect on the biological organisms involved and may seriously interfere with their proper functioning. For years past, in English plants utilizing mechanical types of aerators, such as the Simplex, the Sheffield paddle, and the like, castor oil rather than a mineral oil has been employed for the lubrication of the mechanisms.

Oil and grease are always unsightly in sewage treatment plants, and further they may clog trickling filter nozzles, mechanical distributors, the surface of the stone in trickling filters and the sand surfaces of intermittent sand filters. Mineral oils may and probably sometimes actually do have an inhibiting effect upon the biological organisms associated with trickling and intermittent sand filters.

The mechanical skimming devices operating in conjunction with sludge-removal equipment in sedimentation units have not been altogether satisfactory, due to a number of causes, among which may be mentioned the use of relatively crude and ineffective mechanisms, the adverse effect of winds with uncovered tanks, and the fact that the oil and grease may not rise to the surface within the given period of detention.

It is the writer's belief that even in relatively small plants, and particularly those where the activated sludge process is employed, or where

an effluent is to be salvaged for industrial use, or where a partially treated sewage is to be utilized for irrigation, pre-treatment should be directed toward the effective removal of oil and grease.

A few grease skimming tanks have been introduced in this country within recent years. It is understood that few, if any, of these have been really efficient because of basically poor and inadequate design.

The best method of approach seems to be that first developed and introduced by Dr. Karl Imhoff at the Essen-Rellinghausen plant in Germany, where aeration is employed to bring the oil and grease to the surface and cause it to float and travel laterally past baffles, behind which it will collect and can be removed by skimming or by flotation over weirs. If properly applied the volume of finely divided air required in this scheme of oil and grease flotation is small. The necessary detention period is not long (from 5 to 10 or more minutes, according to circumstances), nor are the structures and mechanisms involved unduly expensive, viewed from the standpoint of accrued benefits.

A very considerable degree of development, both in procedure and removal mechanisms, may be anticipated in the near future.

The removed oil, grease and scum will ordinarily be sent to the digestion tanks with the sludge removed from the sedimentation basins. The effect of oil and grease upon the process of digestion has not as yet been satisfactorily determined. It may be necessary to provide a somewhat more generous storage allowance in digestion tanks to which unusual quantities of oil and grease are delivered.

### Development of Pre-treatment as Related to Sedimentation

It is safe to say that sanitary engineers are placing more and more stress upon effective pre-treatment of sewage. To an increasing extent, final processes of treatment are coming to be regarded as purely oxidizing and/or "polishing" processes, aimed not at the removal of suspended solids but rather at the oxidation of dissolved organic material and colloids which cannot be effectively treated and removed by pre-treatment. As much work as possible should be put upon the pre-treatment devices and as little as possible upon those effecting final treatment. It is expedient and more economical to remove the suspended solids to the greatest reasonable extent by subsidence and to dispose of the sludge by digestion or other means than to allow these solids to be carried through to the point where they must be cared for by the final treatment process.

In general the procedure of subsidence has not yet been made as efficient as it should be and doubtless will be in the near future. More attention is now being given to proper proportioning of tanks, as re-

lated to depth, travel distance and velocities; to detention periods and overflow rates; to inlet and effluent arrangements; and to methods and means of preventing short-circuiting.

Among many other factors, the effective subsidence of settleable solids in sewage depends upon the length of time actually allotted to the process and upon the distance travelled. Engineers are beginning to appreciate the fact, demonstrated theoretically long since, that shallow basins, other things being equal, are more effective per unit of capacity than are deep basins.

The best method of eliminating short circuiting, insofar as basin proportions are concerned, is to provide the greatest reasonable length or distance of forward travel, up to that limit which represents a transporting velocity for the type and size of particle which it is proposed to remove by subsidence. Even under the best conditions of depth vs. length, short circuiting to a degree will occur. It may be reduced appreciably by forcing the sewage to be diffused throughout the cross-sectional area of the basin at the inlet end, and perhaps, if the adopted type of construction and the scum-sludge removal mechanisms will permit, at intermediate points as well. Diffusion baffles of the Sacramento type have proved in numerous cases to be very effective in increasing the efficiency of settling basins, both for sewage and water. If effluent collecting troughs are employed, careful attention must be given to their placement and their length. In general, their length should be considerably greater than that ordinarily found in existing settling basins, either primary or secondary. In some cases orifice flow into such troughs, above the hydraulic grade line therein, will be found to give more uniform results than will weir flow.

Sedimentation basins of most rational and effective depth to meet all other conditions may be disastrously affected by wind. In some parts of the country winds persistently blow at relatively high velocities. Basins which, if covered or otherwise protected from winds, would be very efficient as clarifying devices, are caused to be quite inefficient because of the agitation of their contents by winds. In localities subject to high winds sedimentation basins should be covered, or housed, if possible. Wind breaks of various sorts may be employed where the type of construction does not permit of covers and where housing is economically infeasible.

The matter of the concentration of sludges removed from mechanically cleaned sedimentation basins appears to have received far less attention than it deserves. Extremely wet sludges are commonly withdrawn, whereas more concentrated material could doubtless be produced if proper methods were employed. In the larger sewage treatment works sludge thickening tanks can be utilized, but they would not ordinarily be

expected to be installed at the smaller plants. The German practice of providing deep sludge hoppers appears not to have been largely employed in America. Sludge pumps are frequently of too great capacity and their operation at customary speeds results in the withdrawal of large quantities of water (sewage), with the consequent excessive dilution of the sludge. Improved conditions would result from the use of deeper hoppers, smaller capacity pumps, and adequate means of sampling and of visually observing the condition of the sludge, either before or after pumping.

### Development of Chemical Treatment

Beginning about three years ago, in fact following shortly upon the commercial development and marketing of the ferric coagulants, but perhaps not wholly associated with that fact, a great deal of interest has been aroused among sanitary engineers, chemists and sewage works operators in the chemical treatment of sewage. To date, for the most part, this interest has been expressed in terms of experiment and discussion. A few working plants of various types have been constructed, others are under design, and still others are proposed. It may be anticipated that a considerable number of plants will be constructed within the next few years.

At the present time, and probably always, the chemical treatment of sewage must be regarded as an intermediate process, yielding an effluent of much better appearance and greater stability than can be produced by plain subsidence alone, but generally of less satisfactory appearance and lower stability than effluents from the activated sludge process and trickling filtration, when operating under favorable conditions. However, the effluent of a suitably designed and operated chemical treatment plant is readily amenable to effective disinfection by chlorine and chlorine compounds and when so disinfected may have a stability sufficient to meet rather exacting conditions of ultimate disposal.

It would appear that there are many circumstances and conditions, considering the country at large, where a sewage effluent of the sort that may be produced by chemical treatment will be good enough and will fulfill all local hygienic and esthetic requirements.

It has not yet been demonstrated how uniformly chemical treatment can be made to meet the changing character and varying volume of flow of sewage. Unquestionably, careful control will be found to be essential. In the absence of direct evidence from widely extended experimental and practically operating plants, assurance upon this point must rest at present upon such experimental data as are available, upon the actual operating results of such few plants as have been constructed

and, perhaps, further, upon analogy with the clarification of various types of water by chemical coagulation and subsidence.

It must be remembered that chemical treatment of sewage, as it has been practiced in the United States, was confined to precipitation usually with lime only, but occasionally also with lime and copperas or lime and alum, in old-time plants not provided with modern dosing, mixing and floc-conditioning devices or with mechanical methods of sludge removal. In contrast with such plants, present day chemical treatment plants have the benefit of improved practice and equipment.

Among the various explanations which have been offered of the causes of the new interest in chemical treatment and among the advantages claimed by its proponents, the following are perhaps worthy of note:

(1) the economic conditions of the last several years which have forced municipalities and sanitary districts to find cheaper methods of securing even the minimum of necessary performance;
(2) the recent commercial development and marketing of ferric chloride and perhaps other suitable coagulants at attractive prices;
(3) in contrast with the older methods of "chemical precipitation": (*a*) improved methods of application and mixing of the chemicals and of conditioning the floc; (*b*) improved procedure of sedimentation, especially in small plants; (*c*) improved methods of removing and handling the sludge; (*d*) possibility of sludge digestion;
(4) the simplicity of design and relatively low cost of construction of chemical treatment plants;
(5) the desirability of a type of treatment, intermediate both with respect to performance and costs, as between plain subsidence and final treatment by the activated sludge or trickling filter processes, particularly for seasonal use.

## Sludge Handling and Disposal

*Digestion.*—The thermophilic digestion of sludge, upon which great hopes were placed three or four years ago, does not appear recently to have made much progress in a practical sense. Experimental investigation is still being pursued in some quarters and it is possible that successful results may ultimately be achieved. Its principal disadvantage has been the production of vile odors for which no means of prevention have been as yet discovered. Garbage is being successfully digested by thermogenic thermophiles. This type of organism may perhaps be incapable of utilization in sludge digestion, due to the excessive moisture content of sludge or to other unknown causes.

High-temperature digestion within the mesophilic range, however, continues to make progress and has greatly reduced the period required and, consequently, the capacity or storage requirements of digestion tanks. This development has naturally diverted interest from thermophilic digestion since the shorter time demanded by the latter process can no longer be expected to produce any great economic saving.

Multiple-stage digestion is of comparatively recent origin and appears to offer certain very definite advantages. Whether the optimum number of stages will be two or some larger number remains to be determined by practical experience. The pioneer work of the engineers of the Los Angeles County Sanitation Districts should be acknowledged in this connection.

*Sludge Drying.*—A recent contribution to the art of sludge drying is represented by spray drying devices such as have been installed during the past year at the Joint Plainfield, North Plainfield and Dunellen Works, New Jersey. The economic success of such methods rests not alone upon the mechanism but as well upon a preliminary concentration of the sludge. It is understood that progress is being made with other types of dewatering devices, such as centrifugal driers, and the like. Up to the present time and for several years vacuum drum filtration has proven to be a very effective method of production of workable sludge cake, amenable to disposal by a number of methods. There is good reason to expect continued progress and ultimate success with a variety of devices, each of which may be found to occupy a more or less distinct field of application and usefulness.

*Incineration.*—For a number of years the Chicago Sanitary District has been conducting experiments on a practical scale of various methods of sludge incineration. These investigations are still in progress and it is to be hoped that they will have proceeded to such a stage within the next few months that the results may be made public.

*Sludge As a Fertilizer.*—The drying and grinding of activated sludge by usual methods and its sale as a fertilizer continues. More recently a sludge grinder advertised as a sludge disintegrator and blender has been developed for the purpose of breaking up and making utilizable for fertilizer purposes ordinary digested sludges from drying beds.

## Odor Destruction

The City of Pasadena, California, has under design and construction a heat interchanger for the high-temperature destruction of obnoxious gases created in the process of drying activated sludge for fertilizer production in a common form of rotary drier or kiln. This wholly new device is known as the Cottrell-Royster furnace. The fundamental principles of this furnace were developed by Dr. F. G. Cottrell, Director,

Fixed Nitrogen Research Laboratory, U. S. Department of Agriculture, and by P. H. Royster, Bureau of Mines, U. S. Department of Commerce. The application of this furnace to odor destruction was first demonstrated in the laboratories of the University of California by sanitary engineering students and later in practical tests at Pasadena.

The Pasadena experiment will be watched with interest. If it proves to be successful there will undoubtedly be many possible applications in the sewage works field, particularly where odors from enclosed spaces must be disposed of without creating local nuisances. It will, of course, find many other applications in the broad field of sanitary engineering.

### Salvage of Sewage for Irrigation and Industrial Use

In the semi-arid sections of the country where water is at a premium and relatively high in cost, the treatment of sewage to the point where it can be utilized for irrigation and industrial use continues to make progress. One of the first installations of that sort was at the Grand Canyon, Arizona, in 1926. Here the sewage is treated by the activated sludge process and by subsequent rapid sand filtration and is wholly utilized in locomotive boilers, for the washing of company automobiles, for the flushing of public toilets, for the sprinkling of lawns and for the irrigation of gardens.

# THE RATING OF SEWAGE TREATMENT WORKS. REPORT OF RATING COMMITTEE, NEW YORK STATE SEWAGE WORKS ASSOCIATION

At the Oneonta meeting in October, 1934, the following resolution was unanimously adopted:

"*Resolved*, that a standing committee of three members, to be known as the 'Rating Committee' be appointed, the chairman to be a representative of the Division of Sanitation, State Department of Health. It shall be the duty of this committee to make a report to the January, 1935, meeting of the New York State Sewage Works Association recommending a system of ratings for sewage treatment plants, based on the adequacy of operating data and records, irrespective of size of plant or type of treatment."

Acting under the authority of the above resolution, your committee has given this matter a great deal of careful consideration and study and has the honor to submit the following report.

Your committee believes that it is practical to establish a system of rating that will be fair and equitable to all sewage plant operators, regardless of the size or type of plants under their supervision, and which will enable the operator of a small, simple plant to attain a given rating as readily as the operator of a large and more complex plant. Furthermore, your committee feels that the adoption of such a system and cooperation of all operators in placing the plan in effect will be distinctly in the interests not only of sewage plant operators, but also in the interests of the profession as a whole. It is more than probable that if such a plan is adopted by this Association and whole-hearted cooperation is secured from the operators in this State that the system will promote improvement in the collection of the essential operating data and will serve as a basis for adoption in other states.

In accordance with the foregoing purposes and objectives your committee recommends that the following plan be adopted and placed in effect by the New York State Sewage Works Association.

## Plan for Rating of Sewage Treatment Works According to Adequacy of Operating Data and Records

### General

1. A standing committee to be known as the Rating Committee shall be appointed by the New York State Sewage Works Association to act as the reviewing authority on reports submitted to it.

2. The Rating Committee shall endeavor to enlist the cooperation of operators and to secure the submission of reports conforming in general to the outline or schedule contained in the Appendix attached hereto.

3. The general basis for reports to be submitted to the Rating Committee by plant operators shall be an annual report furnishing pertinent information concerning the plant and summary data for each month of plant operation.

4. As a stimulus for the submission of such reports, a third Kenneth Allen Memorial Award shall be made available annually to the operator receiving the highest rating of the reports submitted, provided, however, that if the operator has already been the recipient of an annual award, such additional award shall be made by title only and the actual award shall be made to the operator receiving the next highest rating of the reports submitted. As a further stimulus for the submission of such reports, the Rating Committee shall write a special complimentary letter to the municipal officials commending each operator who submits a report for his participation in this enterprise.

5. In the interest of disseminating information the Rating Committee should arrange for publication of the reports submitted if feasible. If many reports are submitted the Committee should prepare a summary and have this published. Publication of reports or data submitted to the Rating Committee will be conditioned on consent of local authorities.

6. Ratings of the reports submitted shall be in accordance with the schedule of credits assigned in the attached outline which is based upon the recommendations made by the Committee on Sewage Works Operating and Cost Records of the Federation of Sewage Works Associations as published in the January, 1932, issue of This Journal.

7. In determining the final rating for each report the ratings for Schedules I, II, III, and IV shall be calculated separately, these ratings to comprise the ratio of the total credits assigned by the committee to the total possible credits that would be assigned for a perfect score for whatever treatment processes are employed at the particular plant, thus resolving the separate ratings for each schedule to a percentage basis. The final rating shall be calculated as follows:

To the rating for schedule I, add six times the rating for schedule II, one times the rating for schedule III, and two times the rating for schedule IV, and divide by 10.

8. The Committee is aware that in attempting to devise a rating system applicable to all types of sewage treatment, deficiencies of the proposed system will develop which call for modification from time to time. No change in the numerical rating, however, shall be made without being offered at the annual meeting and voted upon.

### Explanatory

The following condensed summary of the items and credits given in Schedules I, II, III and IV contained in the appendix attached hereto,

and the explanatory remarks which follow will facilitate an understanding of the general principles of the proposed rating system without detailed study of the schedules themselves.

*Condensed Summary of Rating Schedules*

| | No. Items | Credits | Total Credits |
|---|---|---|---|
| **Schedule I**—Descriptive and General | 18 | | 100 |
| **Schedule II**—Operating Data and Practical Control Tests | | | |
| *A*—Grit Chambers | 4 | 50 | |
| *B*—Grease Removal (Separate Process) | 4 | 50 | |
| *C*—Coarse Screens | 4 | 50 | |
| *D*—Fine Screens | 4 | 100 | |
| *E*—Septic Tanks | 8 | 100 | |
| *F*—Primary Sedimentation, Plain Tanks | 8 | 100 | |
| *G*—Primary Sedimentation, Mechanical Tanks | 8 | 100 | |
| *H*—Imhoff Tanks | 14 | 100 | |
| *I*—Dosing Device | 6 | 50 | |
| *J*—Trickling Filters | 8 | 100 | |
| *K*—Contact Beds | 5 | 100 | |
| *L*—Secondary Sedimentation, Plain Tanks | 7 | 100 | |
| *M*—Secondary Sedimentation, Mechanical Tanks | 8 | 100 | |
| *N*—Intermittent Sand Filters | 10 | 100 | |
| *O*—Chlorination | 7 | 100 | |
| *P*—Aeration Tanks (Activated Sludge) | 12 | 100 | |
| *Q*—Sludge Digestion | 12 | 100 | |
| *R*—Sludge Drying Beds | 9 | 100 | |
| *S*—Sludge Analyses | 7 | 100 | |
| *T*—Vacuum Filters for Sludge Dewatering | 11 | 100 | |
| *U*—Vacuum Filters Treating Sewage of Effluent | 11 | 100 | |
| *V*—Incineration | 10 | 100 | |
| *W*—Gas Collection | 4 | 50 | |
| *X*—Gas Utilization | 3 | 50 | |
| *Y*—Chemical Precipitation | 8 | 100 | |
| Total Credits Schedule II | | | 2200 |
| **Schedule III**—Analyses | | | |
| *A*—Raw or Bar-Screened Sewage | 3 | 100 | |
| *B*—Fine Screen Effluent | 2 | 100 | |
| *C*—Settled Effluent | 3 | 100 | |
| *D*—Filtered Effluent | 4 | 100 | |
| *E*—Final Effluent | 4 | 100 | |
| *F*—Stream Above and Below Plant | 5 | 100 | |
| Total Credits Schedule III | | | 600 |
| **Schedule IV**—Cost Data | | | |
| *A*—Original Plant and Additions | 2 | 50 | |
| *B*—Maintenance and Operation | 10 | 100 | |
| Total Credits Schedule IV | | | 150 |

Since the items applicable to each plant are scored on a percentage basis, the perfect score would be:

| | | |
|---|---|---|
| Schedule I | $100 \times 1 =$ | 100 |
| " II | $100 \times 6 =$ | 600 |
| " III | $100 \times 1 =$ | 100 |
| " IV | $100 \times 2 =$ | 200 |
| Total | | 1000 |
| Rating 1/10 of total | = | 100 |

As an example of how the lettered items indicated in the above condensed summary are broken down into separate items in the detailed schedules, items II–*R* and III–*C* will be given as they appear in the schedule contained in the appendix. The other lettered items are similarly broken down into a number of separate items.

**Schedule II**

*R. Sludge Drying Beds*

| Item Reported Upon | Credits |
|---|---|
| 1. Type of beds, number of units, depth sand, and total area | 10 |
| 2. Average depth of dose of wet sludge on bed | 10 |
| 3. pH (average) of sludge as applied to beds | 10 |
| 4. Maximum, minimum and average drying time for sludge | 10 |
| 5. Amount and kind of chemicals used to condition sludge as applied to beds | 10 |
| 6. Cu. ft. wet sludge applied during each month and how measured | 10 |
| 7. Cu. ft. air dried sludge removed during each month and cu. ft. per MG. annually | 20 |
| 8. Disposal of sludge bed drainage | 10 |
| 9 Method of handling and disposal of dried sludge | 10 |
| Total credits for perfect score | 100 |

**Schedule III**

*C. Settled or Clarified Effluent Analyses*

(To be submitted from all plants serving more than 10,000 and from all other plants where the necessary laboratory equipment is provided.)

| Item Reported Upon | Credits |
|---|---|
| 1. General method of sampling | 20 |
| 2. B.O.D. (5 day at 20°) | |
| (*a*) No. of tests made each month | 10 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 10 |
| (*d*) Minimum during each month | 10 |
| 3. Suspended solids | |
| (*a*) No. of tests made each month | 10 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 10 |
| (*d*) Minimum during each month | 10 |
| Total credits for perfect score | 100 |

The following example will indicate how the rating system would be applied to a report covering operation of a plant consisting of a bar screen, primary sedimentation tanks with mechanical sludge removal, sludge digestion tank, gas collection, chlorination, and glass-covered sludge drying beds. The report would in general be expected to follow the outline as given in the Appendix, the data and information being supplied under appropriate headings to enable rapid checking against the items for which credits are given. Where all of the information asked for under each item is given, full credit would be allowed. In case of incomplete or partial answers, credits would be allowed in proportion to the completeness of the data furnished.

Assume that in Schedule I complete data are furnished for all items except items 15, 16 and 17 (which relate to average, maximum, and minimum estimated or measured daily sewage flows). The total allowable credits for these three items are 14 out of a possible 100. Under this assumption, the rating for Schedule I would be 86 per cent.

Items 1 and 2 of Schedule I will indicate the sections of Schedule II which are to be used. In this example the report would be expected to include data and information for the following:

II—*C*. Coarse Screens (4 items with possible credits totaling 50)
*G*. Primary Sedimentation (Tanks with Mechanical Equipment) (8 items with possible credits totaling 100)
*O*. Chlorination (7 items with possible credits totaling 100)
*Q*. Sludge Digestion Tanks (12 items with possible credits totaling 100)
*R*. Sludge Drying Beds (9 items with possible credits totaling 100)
*S*. Sludge Analyses (7 items with possible credits totaling 100)
*W*. Gas Collection (4 items with possible credits totaling 50)
*X*. Gas Utilization (3 items with possible credits totaling 50)

Assume that for Schedule II the report supplies full information and data except for Section *S* and item 3 of Section *W* (Average $CO_2$ content of gas each month). The total possible credits for Sections II—*C*, *G*, *O*, *Q*, *R*, *S*, *W*, and *X* above are 650. Under the foregoing assumption the total credits that would be allowed are 540. The rating for Schedule II would therefore be calculated as 540/650 or 83.1 per cent.

Assume now that the plant serves a population of 5000 and has laboratory equipment for determination of B.O.D.'s but no equipment for suspended solids tests. For Schedule III data would then be expected to be submitted on the following sections:

III—*A*. Raw or Bar Screened Sewage Analyses.
Item 1. (General method sampling, etc.—total possible credits = 20)
Item 2. (B.O.D. data—total possible credits = 40)
Item 3. (suspended solids—no data would be expected)

*C*. Settled or Clarified Effluent Analyses.
Item 1. (total possible credits = 20)
Item 2. (total possible credits = 40)

*F*. Analyses—Stream above and below plant outlet.
Item 1. (total possible credits = 20)
Item 2. (Estimate of stream flow—total possible credits = 20)
Item 3. (B.O.D. data—total possible credits = 20)
Item 4. (D.O. data—total possible credits = 20)
Item 5. (Relative stability data—total possible credits = 20)

Assume that complete data are furnished for all sections in Schedule III except items 4 and 5 of Section *F*. The total possible credits for Schedule III would be 220 and the credits that would be allowed under the above assumptions would be 180. The rating for Schedule III would therefore be calculated as 180/220 or 81.8 per cent.

Assume that for Schedule IV on Cost Data complete data are furnished on all items in Sections *A* and *B*. The rating for Schedule IV would therefore be 150/150 = 100 per cent.

Recapitulating, the ratings for each schedule and the final rating would be as follows:

| | Rating | Weight | Total |
|---|---|---|---|
| Schedule I | 86 | × 1 = | 86.0 |
| Schedule II | 83.1 | × 6 = | 498.6 |
| Schedule III | 81.8 | × 1 = | 81.8 |
| Schedule IV | 100 | × 2 = | 200 |
| | | | 866.4 |

$$\text{Final Rating} = \frac{866.4}{10} = 86.64 \text{ per cent.}$$

Respectfully submitted,

WELLINGTON DONALDSON
JOHN R. DOWNES
A. F. DAPPERT, *Chairman*
*Committee on Rating*

## APPENDIX

### Outline Form of Reports to be Submitted to Rating Committee and Credits to Be Assigned in the Calculation of Final Ratings

#### Schedule I

*Descriptive and General Information*

(Required in all reports regardless of type or size of plant)

| Item Reported Upon | Credits |
|---|---|
| 1. List of all treatment processes in sequence of sewage flow, such as bar screens, fine screens, grit chambers, Imhoff tanks, trickling filters, final settling tanks and chlorination, etc. | 10 |
| 2. List of all-sludge treatment and accessory processes, such as sludge digestion tanks, sludge drying beds, incinerators, vacuum filters, etc. | 10 |
| 3. Gravity flow to plant or is sewage or effluent pumped? Explain. | 4 |
| 4. Date plant was placed in operation | 4 |
| 5. Design basis of original sewage works as to volume of sewage to be treated and population to be served | 8 |
| 6. Date and nature of subsequent additions | 4 |
| 7. Present population served and how obtained | 8 |
| 8. Separate or combined sewers and percentage of each | 5 |
| 9. Storm water diversion outlets or bypasses and the number of days each month such devices are in operation | 4 |
| 10. Nature and importance of industrial wastes tributary to sewage works | 5 |
| 11. Method of measuring or estimating sewage flow | 5 |
| 12. General purpose of sewage treatment such as protection of down-stream water supply, prevent nuisance conditions, etc. | 4 |
| 13. Are separate meters available at plant for proportioning power consumed by various processes? | 5 |
| 14. Total electric power used each month in K.W.H. and power used separately by each unit in treatment process for which a separate meter is available | 6 |
| 15. Average daily sewage flow entering plant for each month | 6 |
| 16. Maximum daily sewage flow entering plant in each month | 4 |
| 17. Minimum daily sewage flow entering plant in each month | 4 |
| 18. List of employees at plant and approximate time spent by each in operating or maintaining plant | 4 |
| Total credits in Schedule I for perfect score | 100 |

#### Schedule II

*Operating Data and Practical Control Tests*

(Rating shall be applied to all of those sections indicated by items 1 and 2 in Schedule I. Omit rating on the sections below which do not apply)

*A. Grit Chambers*

| Item Reported Upon | Credits |
|---|---|
| 1. Type of grit chamber or detritor, average velocity, average detention period, and number of units | 10 |
| 2. Frequency of grit removal or grit chamber cleaning | 10 |

| | |
|---|---|
| 3. Cubic feet of grit removed each month and cu. ft. per M.G. | 20 |
| 4. Method of handling and grit disposal | 10 |
| Total credits for perfect score | 50 |

*B. Grease Removal* (If separate from and in addition to items *E*, *F*, and *G* of this schedule)

| Item Reported Upon | Credits |
|---|---|
| 1. Type of device. Describe essential features | 10 |
| 2. Frequency of grease removal | 10 |
| 3. Cubic feet of grease removed each month and cu. ft. per M.G. | 20 |
| 4. Method of handling and disposal of grease | 10 |
| Total credits for perfect score | 50 |

*C. Coarse Screens*

| Item Reported Upon | Credits |
|---|---|
| 1. Type of screen, number of units, and clear openings between bars | 10 |
| 2. Frequency of screenings removal | 10 |
| 3. Cubic feet of screenings removed each month and cubic feet per M.G. | 20 |
| 4. Method of handling and disposal of screenings | 10 |
| Total credits for perfect score | 50 |

*D. Fine Screens*

| Item Reported Upon | Credits |
|---|---|
| 1. Type of screen, rated capacity, number of units, and clear openings | 25 |
| 2. Cubic feet of screenings removed each month and cubic feet per M.G. | 30 |
| 3. Method of handling and disposal of screenings | 25 |
| 4. Average dry solids content of screenings removed each month | 20 |
| Total credits for perfect score | 100 |

*E. Septic Tanks*

| Item Reported Upon | Credits |
|---|---|
| 1. Type of tanks, total capacity and number of units | 10 |
| 2. Detention period based on average sewage flow | 10 |
| 3. Frequency of sludge removal | 10 |
| 4. Cubic feet of sludge and scum removed each year and cubic feet per M.G. | 20 |
| 5. Depth of sludge in tank each month | 10 |
| 6. Depth of scum in tank each month | 10 |
| 7. Settleable solids in influent—c.c. per liter (1 hr.) | |
| (*a*) Number of tests made during each month | 3 |
| (*b*) Average of all readings for each month | 4 |
| (*c*) Maximum reading during each month | 4 |
| (*d*) Minimum reading during each month | 4 |
| 8. Settleable solids in effluent—c.c. per liter (1 hr.) | |
| (*a*) Number of tests made during each month | 3 |
| (*b*) Average of all readings for each month | 4 |
| (*c*) Maximum reading during each month | 4 |
| (*d*) Minimum reading during each month | 4 |
| Total credits for perfect score | 100 |

*F. Primary Sedimentation* (plain tanks—separate digestion)

| Item Reported Upon | Credits |
|---|---|
| 1. Type of tanks, capacity and number of units | 10 |
| 2. Detention period based on average sewage flow | 5 |
| 3. Frequency of sludge withdrawal to digestor | 5 |
| 4. Frequency of scum removal | 5 |
| 5. Cu. ft. of sludge removed each month and cu. ft. per M.G. | 25 |
| 6. Cu. ft. of scum removed each month and cu. ft. per M.G. | 10 |
| 7. Settleable solids in influent—c.c. per liter (1 hr.) | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average of daily readings for each month | 5 |
| (*c*) Maximum reading during each month | 5 |
| (*d*) Minimum reading during each month | 5 |
| 8. Settleable solids in effluent—c.c. per liter (1 hr.) | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average of daily readings for each month | 5 |
| (*c*) Maximum reading during each month | 5 |
| (*d*) Minimum reading during each month | 5 |
| Total credits for perfect score | 100 |

*G. Primary Sedimentation* (tanks with mechanical equipment)

| Item Reported Upon | Credits |
|---|---|
| 1. Type of tanks, mechanical equipment, capacity and number of units | 10 |
| 2. Detention period based on average sewage flow | 10 |
| 3. Frequency and average daily time sludge mechanism operated | 10 |
| 4. Frequency of sludge withdrawal to digestor | 10 |
| 5. Cubic feet of sludge removed during each month and cubic feet per M.G. | 10 |
| 6. Cubic feet of skimmings removed during each month and cubic feet per M.G. | 10 |
| 7. Settleable solids in influent—c.c. per liter (1 hr.) | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average of daily readings for each month | 5 |
| (*c*) Maximum daily reading during each month | 5 |
| (*d*) Minimum daily reading during each month | 5 |
| 8. Settleable solids in effluent—c.c. per liter (1 hr.) | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average of daily readings for each month | 5 |
| (*c*) Maximum daily reading during each month | 5 |
| (*d*) Minimum daily reading during each month | 5 |
| Total credits for perfect score | 100 |

*H. Imhoff Tanks*

| Item Reported Upon | Credits |
|---|---|
| 1. Type of tanks, settling capacities and number of units | 5 |
| 2. Detention period based on average sewage flow | 5 |
| 3. Total available sludge digestion capacity, 18″ below slot—cu. feet | 5 |
| 4. Frequency of sludge withdrawal | 2 |
| 5. Cu. ft. of sludge removed each month and cu. ft. per M.G. annually | 10 |
| 6. Total sludge in tanks each month (cu. ft.) | 10 |
| 7. Depth of scum in gas vents each month | 3 |

| | |
|---|---|
| 8. Average pH of sludge in tank each month | 5 |
| 9. Frequency of squeegeeing, skimming, hosing, etc. | 2 |
| 10. Cu. ft. of skimmings removed each month and cu. ft. per M.G. | 5 |
| 11. Method of disposal of skimmings and gas vent scum | 3 |
| 12. Kind and amounts of chemicals used to aid digestion each month | 5 |
| 13. Settleable solids in influent—c.c. per liter (1 hr.) | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average of daily readings for each month | 5 |
| (*c*) Maximum daily reading for each month | 5 |
| (*d*) Minimum daily reading in each month | 5 |
| 14 Settleable solids in effluent—c.c. per liter 1 (hr.) | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average of daily readings for each month | 5 |
| (*c*) Maximum daily reading in each month | 5 |
| (*d*) Minimum daily reading in each month | 5 |
| Total credits for perfect score | 100 |

*I. Dosing Device*

| Item Reported Upon | Credits |
|---|---|
| 1. Type (single, or twin, etc.), capacity, no. of units, etc. | 10 |
| 2. No. of siphons in each unit and alternating arrangement | 5 |
| 3. Average time required for dosing tank to fill | 10 |
| 4. Average time required for dosing tank discharge | 10 |
| 5. Average time between doses | 10 |
| 6. Frequency of cleaning | 5 |
| Total credits for perfect score | 50 |

*J. Trickling Filters*

| Item Reported Upon | Credits |
|---|---|
| 1. Type and number of units | 10 |
| 2. Area and depth of filter | 10 |
| 3. Size and kind of filter media | 10 |
| 4. Type of distributors, nozzles, etc. | 10 |
| 5. Frequency and extent of nozzle and distributor cleaning | 10 |
| 6. Condition of bed with reference to pooling, growths, ice, flies, odors, etc., each month | 10 |
| 7. Settleable solids in effluent—c.c. per liter (1 hr.) | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average daily reading for each month | 5 |
| (*c*) Maximum daily reading in each month | 5 |
| (*d*) Minimum daily reading for each month | 5 |
| 8. Relative stability of effluent | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average stability during month | 5 |
| (*c*) Maximum stability during month | 5 |
| (*d*) Minimum stability during month | 5 |
| Total credits for perfect score | 100 |

*K. Contact Beds*

| Item Reported Upon | Credits |
|---|---|
| 1. Area, depth and number of beds | 10 |
| 2. Size and kind of filter media | 10 |
| 3. Contact period | 10 |
| 4. Settleable solids in effluent—c.c. per liter (1 hr.) | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average daily reading in each month | 10 |
| (*c*) Maximum daily reading for each month | 10 |
| (*d*) Minimum daily reading for each month | 10 |
| 5. Relative stability of effluent | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average stability during each month | 10 |
| (*c*) Maximum stability during each month | 10 |
| (*d*) Minimum stability during each month | 10 |
| Total credits for perfect score | 100 |

*L. Secondary Sedimentation* (plain tanks)

| Item Reported Upon | Credits |
|---|---|
| 1. Type of tanks, capacity and no. of units | 10 |
| 2. Detention period based on average sewage flow | 10 |
| 3. Frequency of sludge withdrawal | 10 |
| 4. Cu. ft. of sludge removed each month and cu. ft. per M.G. | 20 |
| 5. Disposal of sludge | 10 |
| 6. Settleable solids in effluent—c.c. per liter (1 hr.) | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average daily reading during each month | 5 |
| (*c*) Maximum daily reading during each month | 5 |
| (*d*) Minimum daily reading during each month | 5 |
| 7. Relative stability | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average stability during each month | 5 |
| (*c*) Maximum stability during each month | 5 |
| (*d*) Minimum stability during each month | 5 |
| Total credits for perfect score | 100 |

*M. Secondary Sedimentation* (mechanical equipment)

| Item Reported Upon | Credits |
|---|---|
| 1. Type of tanks, mechanical equipment, capacity, and number of units | 10 |
| 2. Detention period based on average sewage flow | 10 |
| 3. Frequency and average daily time sludge mechanism operated | 5 |
| 4. Frequency of sludge withdrawal | 5 |
| 5. Cu. ft. of sludge removed during each month and cu. ft. per M.G. | 20 |
| 6. Disposal of sludge | 10 |
| 7. Settleable solids in effluent—c.c. per liter (1 hr.) | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average daily reading during each month | 5 |
| (*c*) Maximum daily reading during each month | 5 |
| (*d*) Minimum daily reading during each month | 5 |

| | |
|---|---|
| 8. Relative stability of effluent | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average daily reading during each month | 5 |
| (*c*) Maximum daily reading during each month | 5 |
| (*d*) Minimum daily reading during each month | 5 |
| Total credits for perfect score | 100 |

*N. Intermittent Sand Filters*

| Item Reported Upon | Credits |
|---|---|
| 1. Type and number of units | 10 |
| 2. Area and depth of filter | 5 |
| 3. Kind and size of filter media | 5 |
| 4. Method and frequency of bed scraping, conditioning, cleaning, etc. | 10 |
| 5. Cu. ft. sand removed annually | 10 |
| 6. Cu. ft. sand replaced annually | 10 |
| 7. Million gallons of sewage applied per acre between rest periods | 10 |
| 8. Average period filter units are out of service for cleaning | 10 |
| 9. Condition of bed with reference to clogging, pooling, ice, etc., each month | 10 |
| 10. Relative stability of effluent | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average stability during each month | 5 |
| (*c*) Maximum stability during each month | 5 |
| (*d*) Minimum stability during each month | 5 |
| Total credits for perfect score | 100 |

*O. Chlorination.* (Data for item 7 must be supplied to receive full credit when in judgment of Committee *B. coli* tests are regarded as essential.)

| Item Reported Upon | Credits |
|---|---|
| 1. Type of equipment and no. of units | 10 |
| 2. Points of application | 10 |
| 3. General purpose of chlorine treatment | 10 |
| 4. Lbs. chlorine used each month and lbs. per M.G. | 15 |
| 5. Contact period for chlorine reaction | 5 |
| 6. Residual chlorine (p.p.m.) | 5 |
| (*a*) Frequency of residual chlorine tests | 5 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 10 |
| (*d*) Minimum during each month | 10 |
| 7. Statement relative to method and frequency of making *B. coli* tests on final effluent | 10 |
| Total credits for perfect score | 100 |

*P. Aeration Tanks* (activated sludge)

| Item Reported Upon | Credits |
|---|---|
| 1. Type of tanks, depth below flow line, type and depth of diffusors, of tanks, and no. of units | 5 |
| 2. Aeration period based upon average sewage flow plus returned sludge | 5 |
| 3. Air used per gallon of sewage flow for each month | 5 |

| | |
|---|---|
| 4. Ratio of sludge returned to average sewage flow each month | 5 |
| 5. Settleable solids in aeration tanks. Percent by volume settling in ½ hr. | |
| (*a*) Frequency of tests | 3 |
| (*b*) Average during each month | 4 |
| (*c*) Maximum during each month | 4 |
| (*d*) Minimum during each month | 4 |
| 6. Suspended solids in aeration tanks—p.p.m. | |
| (*a*) Frequency of tests | 3 |
| (*b*) Average during each month | 4 |
| (*c*) Maximum during each month | 4 |
| (*d*) Minimum during each month | 4 |
| 7. Suspended solids in returned sludge—p.p.m. | |
| (*a*) Frequency of tests | 3 |
| (*b*) Average during each month | 4 |
| (*c*) Maximum during each month | 4 |
| (*d*) Minimum during each month | 4 |
| 8. Suspended solids in secondary clarifier effluent | |
| (*a*) Frequency of tests | 3 |
| (*b*) Average during each month | 4 |
| (*c*) Maximum during each month | 4 |
| (*d*) Minimum during each month | 4 |
| 9. Air pressure at compressor discharge or R.P.M. of mechanical aerators | 5 |
| 10. Excess sludge | |
| (*a*) Total cu. ft. removed monthly, cu. ft. per M.G. annually and method of disposal | 5 |
| 11. Information on frequency and extent of sludge bulking | 5 |
| 12. Sludge index (Mohlman's—see SEWAGE WORKS JOURNAL (1934) 6: 21) Average and range during each month | 5 |
| Total credits for perfect score | 100 |

*Q. Sludge Digestion Tanks*

| Item Reported Upon | Credits |
|---|---|
| 1. Type of digestion tank, no. of units, total capacity, and appurtenances | 10 |
| 2. Digestion capacity actually used, based on average liquid level in tanks | 10 |
| 3. Average digestion temperature of sludge each month | 10 |
| 4. Average pH of sludge each month | 10 |
| 5. Kind and amounts of chemicals used to aid digestion monthly | 10 |
| 6. Average volume of heating water used daily | 5 |
| 7. Average temperature of heating water to digestor for each month | 5 |
| 8. Average temperature of heating water from digestor for each month | 5 |
| 9. Cu. ft. of sludge removed from digestor each month and cu. ft. per M.G. annually | 20 |
| 10. Cu. ft. of sludge in tanks each month | 5 |
| 11. Sludge liquor (supernatant)—method of disposal | 5 |
| 12. Comments with reference to operating difficulties | 5 |
| Total credits for perfect score | 100 |

*R. Sludge Drying Beds*

| Item Reported Upon | Credits |
|---|---|
| 1. Type of beds, number of units, depth sand, and total area | 10 |
| 2. Average depth of dose of wet sludge on bed | 10 |

| | |
|---|---|
| 3. pH (average) of sludge as applied to beds | 10 |
| 4. Maximum, minimum and average drying time for sludge | 10 |
| 5. Amount and kind of chemicals used to condition sludge as applied to beds | 10 |
| 6. Cu. ft. wet sludge applied during each month and how measured | 10 |
| 7. Cu. ft. air dried sludge removed during each month and cu. ft. per M.G. annually | 20 |
| 8. Disposal of sludge bed drainage | 10 |
| 9. Method of handling and disposal of dried sludge | 10 |
| Total credits for perfect score | 100 |

*S. Sludge Analyses*

| Item Reported Upon | Credits |
|---|---|
| 1. State frequency of sampling and facilities for measurements and weighings | 15 |
| 2. Dry solids % in primary sludge (except Imhoff, plain and septic tanks) | 10 |
| 3. Dry solids % in digested sludge to beds or lagoons | 10 |
| 4. Dry solids % in air dried sludge from beds | 5 |
| 5. Average pounds (dry basis) of raw sludge solids per M.G. sewage treated, annually | 20 |
| 6. Average pounds (dry basis) of digested sludge solids per M.G. sewage treated, annually | 20 |
| 7. Average pounds per capita daily of raw solids recovered as sludge, annually | 20 |
| Total credits for perfect score | 100 |

*T. Vacuum Filters for Sludge Dewatering*

| Item Reported Upon | Credits |
|---|---|
| 1. Type of filter, dimensions, number of units and total filtering area | 10 |
| 2. Vacuum maintained on filter | 5 |
| 3. No. days filter operated each month | 5 |
| 4. No. filter hours during each month (sum of all units) | 5 |
| 5. Chemicals used for conditioning in lbs. per 100 lbs. of dry sewage solids | 10 |
| 6. Average thickness of filter cake, inches | 5 |
| 7. Pounds of wet filter cake produced monthly | 10 |
| 8. Dry solids content of filter cake, % | 15 |
| 9. Equivalent lbs. of dry solids in cake monthly and lbs. per M.G. sewage flow | 15 |
| 10. Yield, dry sewage solids Lbs./Sq. Ft./Hr. | 10 |
| 11. Method of handling and disposal of cake | 10 |
| Total credits for perfect score | 100 |

*U. Vacuum Filters for Treating Sewage or Effluent*

| Item Reported Upon | Credits |
|---|---|
| 1. Type of filter, dimensions, number of units and total filtering area | 10 |
| 2. No. days filters operated during month | 5 |
| 3. No. filter hours during month (sum of all units) | 5 |
| 4. Vacuum maintained on filter | 5 |
| 5. Chemicals or filter medium, pounds used monthly and pounds per M.G. | 15 |
| 6. Average thickness of filter cake, inches | 5 |
| 7. Pounds of wet cake monthly and pounds per M.G. | 15 |
| 8. Dry solids content of filter cake | 10 |

| | |
|---|---|
| 9. Suspended solids of influent, p.p.m., average monthly | 10 |
| 10. Suspended solids of effluent, p.p.m., average monthly | 10 |
| 11. Method of handling and disposal of filter cakes | 10 |
| Total credits for perfect score | 100 |

*V. Incineration*

| Item Reported Upon | Credits |
|---|---|
| 1. Type, number of units and rated capacity | 10 |
| 2. Temperature in combustion chamber (average) | 5 |
| 3. Preliminary drying or dewatering arrangements and results of treatment | 10 |
| 4. Amount and kind of auxiliary fuel used, per ton of dry solids | 10 |
| 5. Tons of wet sludge or screenings fed each month | 20 |
| 6. Average dry solids and volatile content of sludge or screenings as fed | 15 |
| 7. Tons of dry sludge or screenings solids per M.G. of sewage flow monthly | 10 |
| 8. Average daily time incinerator is in operation | 5 |
| 9. Average volatile content of incinerator ash | 5 |
| 10. Comments on operating difficulties | 10 |
| Total credits for perfect score | 100 |

*W. Gas Collection*

| Item Reported Upon | Credits |
|---|---|
| 1. Type of collector, gas-holder, appurtenances, etc. | 15 |
| 2. Cu. ft. of gas produced | |
| (*a*) Average daily for each month | 10 |
| (*b*) Maximum daily for each month | 5 |
| (*c*) Minimum daily for each month | 5 |
| 3. Average $CO_2$ content of gas each month | 10 |
| 4. Gas pressure at meter | 5 |
| Total credits for perfect score | 50 |

*X. Gas Utilization*

| Item Reported Upon | Credits |
|---|---|
| 1. General uses made of gas | 10 |
| 2. Type of equipment, capacities, etc. for each unit utilizing gas | 20 |
| 3. Average daily cu. ft. of gas used in each unit for each month | 20 |
| Total credits for perfect score | 50 |

*Y. Chemical Precipitation*

| Item Reported Upon | Credits |
|---|---|
| 1. Total lbs. and lbs. per M.G. of each chemical used each month | 20 |
| 2. Feeding equipment, mixing device, etc. | 20 |
| 3. Points of application of chemicals | 10 |
| 4. Detention period of mixing for average sewage flow | 10 |
| 5. Velocity, rapidity of mixing | 10 |
| 6. pH of influent (average) before chemicals added | 10 |
| 7. pH of effluent (average) | 10 |
| 8. General comments relative to coagulation | 10 |
| Total credits for perfect score | 100 |

## Schedule III

*Analyses*

*A. Raw or Bar-Screened Sewage Analyses.* (State which)

(To be submitted from all plants serving more than 10,000 and from all other plants where the necessary laboratory equipment is provided. For fine screening plants omit B.O.D. of raw sewage.)

| Item Reported Upon | Credits |
|---|---|
| 1. General method of sampling and outline of procedure | 20 |
| 2. B.O.D. (5 day at 20°) | |
| (*a*) No. of tests made each month | 10 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 10 |
| (*d*) Minimum during each month | 10 |
| 3. Suspended solids | |
| (*a*) No. of tests made each month | 10 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 10 |
| (*d*) Minimum during each month | 10 |
| Total credits for perfect score | 100 |

*B. Fine Screen Effluent*

| Item Reported Upon | Credits |
|---|---|
| 1. General method of sampling | 20 |
| 2. Suspended solids | |
| (*a*) No. of tests made each month | 20 |
| (*b*) Average during each month | 30 |
| (*c*) Maximum during each month | 15 |
| (*d*) Minimum during each month | 15 |
| Total credits for perfect score | 100 |

*C. Settled or Clarified Effluent Analyses*

(To be submitted from all plants serving more than 10,000 and from all other plants where the necessary laboratory equipment is provided.)

| Item Reported Upon | Credits |
|---|---|
| 1. General method of sampling | 20 |
| 2. B.O.D. (5 day at 20°) | |
| (*a*) No. of tests made each month | 10 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 10 |
| (*d*) Minimum during each month | 10 |
| 3. Suspended solids | |
| (*a*) No. of tests made each month | 10 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 10 |
| (*d*) Minimum during each month | 10 |
| Total credits for perfect score | 100 |

*D. Filtered Effluent Analyses*

(To be submitted from all plants serving more than 10,000 and from all other plants where the necessary laboratory equipment is provided.)

| Item Reported Upon | Credits |
|---|---|
| 1. General method of sampling | 10 |
| 2. B.O.D. (5 day at 20°) | |
| (*a*) No. of tests made each month | 10 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 5 |
| (*d*) Minimum during each month | 5 |
| 3. Suspended solids (except for intermittent sand filters) | |
| (*a*) No. of tests made each month | 10 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 5 |
| (*d*) Minimum during each month | 5 |
| 4. Dissolved oxygen | |
| (*a*) No. of tests made each month | 10 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 5 |
| (*d*) Minimum during each month | 5 |
| Total credits for perfect score | 100 |

*E. Final Tank Effluent Analyses*

(To be submitted from all plants serving more than 10,000 and from all other plants where the necessary laboratory equipment is provided.)

| Item Reported Upon | Credits |
|---|---|
| 1. General method of sampling | 10 |
| 2. B.O.D. (5 day at 20°) | |
| (*a*) No. of tests made each month | 10 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 5 |
| (*d*) Minimum during each month | 5 |
| 3. Suspended solids (except for intermittent sand filters) | |
| (*a*) No. of tests made each month | 10 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 5 |
| (*d*) Minimum during each month | 5 |
| 4. Dissolved oxygen | |
| (*a*) No. of tests made each month | 10 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 5 |
| (*d*) Minimum during each month | 5 |
| Total credits for perfect score | 100 |

*F. Analyses—Stream Above and Below Plant Outlet*

(To be submitted from all plants serving more than 10,000 and from all other plants where the necessary laboratory equipment is provided, and where such tests in judgment of Committee are significant)

| Item Reported Upon | Credits |
|---|---|
| 1. General method of sampling | 20 |
| 2. Estimate of average monthly flow of stream and how obtained | 20 |
| 3. Average B.O.D. each month and number of tests | 20 |
| 4. Average D.O. each month and number of tests | 20 |
| 5. Average relative stability and number of tests | 20 |
| Total credits for perfect score | 100 |

**Schedule IV**

*Cost Data*

*A. Original Plant Cost*

| Item Reported Upon | Credits |
|---|---|
| 1. Original cost of plant excluding intercepting sewers and pumping stations not located on plant site | 25 |
| 2. Original cost of additions or modifications | 25 |
| Total credits for perfect score | 50 |

*B. Maintenance and Operation Costs for the Year*

| Item Reported Upon | Credits |
|---|---|
| 1. Salary of person in charge of plant | 10 |
| 2. Total salaries of chemists, clerks or office personnel | 10 |
| 3. Total wages of all other laborers and employees proportioned in accordance with time devoted to plant operation and maintenance | 10 |
| 4. Total power costs, itemized according to units, such as pumping, lights, etc. | 10 |
| 5. Total cost for chemicals, itemized according to chemicals used | 10 |
| 6. Total for miscellaneous or other costs. (Itemize if possible) | 10 |
| 7. Grand total of all expenses during year for operation and maintenance | 10 |
| 8. Revenue from sale of sludge, etc. | 10 |
| 9. Net total operating and maintenance expense for year | 10 |
| 10. Average cost per M.G. of sewage treated during year | 10 |
| Total credits for perfect score | 100 |

# Industrial Wastes

## MEASURES OF NATURAL OXIDATION IN POLLUTED STREAMS. I. THE OXYGEN DEMAND FACTOR

By H. W. Streeter

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The ability of natural bodies of water to assimilate organic polluting matters has long been recognized as being due to oxidation processes, largely bio-chemical in their nature, which bring about a gradual stabilization of these impurities through their transformation into humus and simple oxidized products of carbon and nitrogen. As oxygen is the dominant motivating factor in these processes, efforts to study them quantitatively have been aimed primarily at observing the progressive changes which occur in this element, both free and combined, in connection with natural purification phenomena.

From the classic studies made by Adeney [1] in Great Britain and by Phelps [2] in this country some 25 years ago, a basis was established for measuring natural oxidation phenomena by laboratory methods involving the use of tests for dissolved oxygen (D.O.) and bio-chemical oxygen demand (B.O.D.), which tests have been extensively applied in connection with the control of artificial sewage treatment. Although the technique and interpretation of these tests have been steadily improved through the extensive research work of Theriault [3] and others, their application to the measurement of oxidation in polluted natural bodies of water has been met by numerous difficulties, owing to the great complexity and variability of conditions in nature which tend to modify the normal course of this phenomenon.

These difficulties have led the Public Health Service, in connection with its stream pollution investigations, to devote considerable attention to the more fundamental aspects of natural oxidation in polluted streams, having in mind the great practical importance of this phase of the problem in relation to utilizing the natural purification capacities of rivers which must be used as carriers of raw and treated sewage and at the same time for other essential purposes, such as water supply, navigation, fish conservation and various recreational activities.

The first basic study of this kind undertaken by the Public Health Service was made in connection with an extensive laboratory survey of the Ohio River in 1914–16.[4] In their report [5] of this study, Streeter and

Phelps formulated a working theory of stream oxidation, based on the progressive change in dissolved oxygen content of the stream proper resulting from concurrent deoxygenation and atmospheric reaeration. This general theory was applied later by a Board of Engineering Review for the Sanitary District of Chicago, in connection with a study [6] of oxidation data obtained by the Public Health Service in 1921–22 from a laboratory survey of the Illinois River.[7] It also has been utilized more recently by Setter,[8] by Ridenour,[9] and by Phelps and Velz [18] in connection with their studies of natural purification in polluted bodies of water located near the Atlantic seaboard.

In two papers [10, 11] written subsequently to the original report with Phelps on the Ohio River study, the present writer undertook to discuss some of the practical difficulties involved in measuring oxidation in polluted streams, noting the complicating effects of sludge deposits and of the presence of an "immediate" or "chemical" oxygen demand in highly polluted streams. In their report of their Illinois River study, the Chicago Board of Engineering Review endeavored to minimize some of these difficulties by utilizing the concept of a changing "oxygen balance" in polluted streams, the term "balance" signifying the difference between oxygen supply, as represented by the measured dissolved oxygen content, and oxygen demand, as measured by the loss of oxygen in samples of river water incubated under standard conditions of time and temperature (now commonly denoted as the test for bio-chemical oxygen demand, or B.O.D.).

Within the past two years, the present writer, with the assistance of Mr. C. T. Wright of the staff of the U. S. Public Health Service's Station of Stream Pollution Investigations at Cincinnati, has undertaken a further study of certain phases of this problem bearing more especially on the difficulties involved in the practical measurement of natural stream oxidation. In order to lay the groundwork for the presentation of the results of this study in later reports of this series, two preliminary papers have been prepared, both dealing with the more fundamental aspects of the problem. The present paper, the first of the series, will deal with the basic principles underlying the measurement and interpretation of progressive changes in the bio-chemical oxygen demand of polluted stream waters and will consider also some of the more important factors which modify these changes.

*Basic Principles Underlying Natural Oxidation Phenomena.*—Under natural conditions, or under laboratory conditions approaching those of nature, the bio-chemical oxidation of organic substances into simple oxidized products appears to be accomplished very largely as the result of bacterial action, probably through the formation of intermediate enzymes, on these organic substances as a part of the normal life processes

of certain types of bacteria. As is well known, different groups of bacteria function in the presence and in the absence of oxygen, and different end-products are formed. The oxidation activity of the bacteria appears to be modified considerably by other biological agents, such as the bacteria-consuming plankton, and also by certain physical conditions, such as temperature, which affect their growth rate and equilibrium. It has been shown by Butterfield, Purdy and Theriault,[12] that under experimental conditions the rate of bio-chemical oxidation is closely related to bacterial activity, which in turn is stimulated by any biological or physical action tending to keep the number of bacteria below their saturation point.

It was demonstrated by Adeney,[1] that natural oxidation occurs in two distinct stages, the first involving oxidation of the carbonaceous matter, and the second, that of the nitrogenous material. It has been shown by Phelps [2] and Theriault,[3] that the first of these two stages, which merges into the second, tends to follow a course similar to that of monomolecular chemical reactions, whereby at a given temperature a constant proportion of the remaining unoxidized substance is oxidized in each equal interval of time. For first-stage or carbon-oxidation, this law has been expressed by Theriault [3] thus:

$$\text{Ln}\frac{L_t}{L} = -Kt, \qquad \text{or} \qquad \text{Log}\frac{L_t}{L} = -kt$$

where $(L)$ is the initial bio-chemical oxygen demand (B.O.D.), $(L_t)$ the demand remaining after any time $(t)$ within the first stage of oxidation and $K$ $(= 2.3k)$ a constant defining the specific rate of oxidation.*

These relationships also may be expressed as

$$L_t = L \cdot e^{-Kt} = L \cdot 10^{-kt} \tag{1}$$

where $(e)$ is the Naperian logarithmic base and (10) the base of the common or Briggs system of logarithms.

It was found empirically by Phelps and the writer [5] that the value of the constant $(k)$ varies with temperature according to the relation:

$$\frac{k_{T'}}{k_T} = \theta^{(T'-T)} \tag{2}$$

where $(k_{T'})$ and $(k_T)$ are values of the constant at two different temperatures $(T')$ and $(T)$, respectively, and $(\theta)$ a thermal constant, which they determined experimentally as being equal to 1.047 for temperatures

* This system of nomenclature is similar to that proposed by Phelps in connection with Theriault's monograph (3) and will be followed hereafter, except that additional subscripts will be used with the general symbol $(L)$ to designate specific amounts of B.O.D. observed in the stream and at different temperatures.

ranging from 10 to 37 degrees Centigrade. This value of ($\theta$) was approximately confirmed by the results of later experiments by Theriault,[3] who also showed the analogy existing between relation (2) and the van't Hoff-Arrhenius equation:

$$\text{Log}\frac{k_{T'}}{k_T} = \frac{\mu(T'-T)}{2.3026R(T'-273)(T-273)} \qquad (3)$$

where ($R$) is the gas constant 1.9885, ($\mu$) the heat of activation, and the other terms as in equation (2).

From an analysis of data obtained by several observers, Theriault found that the value of the heat of activation constant ($\mu$) ranged from 7400 to 8500, the values obtained with ($\theta$) equal to 1.047 being 7620 for temperatures ranging from 10 to 20 degrees Centigrade and 8080 between 20 and 30 degrees. The analogy between equations (2) and (3) was shown by noting that within a narrow range of temperature the value of

$$\frac{\mu}{2.3026R(T'-273)(T-273)} = N$$

is substantially a constant. Substituting this constant ($N$) in (3), we have that

$$\text{Log}\frac{k_{T'}}{k_T} = N(T'-T)$$

from which

$$\frac{k_{T'}}{k_T} = 10^{N(T'-T)} = \theta^{(T'-T)}$$

where $\theta = 10^N = 1.047$.

It may be noted in this connection that the results obtained by Theriault [3] from his extensive laboratory studies also confirmed those of Adeney with respect to the course of two-stage oxidation. Theriault further has shown from his own observations that the course of two-stage oxidation is accelerated with increase in temperature and that the total bio-chemical oxygen demand at each stage is greater as the temperature is raised. He has derived the following empirical formula connecting variations in the total first-stage oxygen demand ($L$) with temperature:

$$L_T = L_{20}[0.02T - 0.60] = L_{20}[1 - 0.02(T - 20)] \qquad (4)$$

where $L_T$ = Value of $L$ at $T°$ C. $L_{20}$ = Value of $L$ at 20° C.

The foregoing relationships have been found to hold consistently under laboratory conditions, when the three necessary elements, (1) oxidizable matter, (2) oxidizing micro-organisms, and (3) an available source of oxygen, are present concurrently. If any one of these three

elements be absent, as for example in a sterile sewage, or in the absence of oxygen, then bio-chemical oxidation cannot follow a normal course, though it can be brought back to a normal condition in most cases by making up a deficiency in one or more of the three elements.

It may be further noted that from the results of recent studies by Theriault and McNamee,[13] it has appeared that under aerobic conditions, the oxidation of sewage sludge proceeds in accordance with the same laws and at the same rates as does the oxidation of the supernatant liquid portion of sewage or other similar organic waste. These workers also have observed that where sewage sludge or sewage-polluted water has undergone anaerobic decomposition, certain readily oxidizable products are formed which apparently combine directly with dissolved oxygen when brought into contact with it, causing an "immediate" or "enzymic" oxygen demand, as distinguished from the bio-chemical demand exerted under aerobic conditions. The specific rate at which this chemical oxygen demand is satisfied has been found by Theriault and McNamee,[13] to be roughly 16 times the normal bio-chemical rate at 20° C. and also to vary with the temperature. Although their data suggest the possibility that variations in temperature may influence the rate of oxidation of the "immediate" demand to a slightly less extent than they affect that of the "bio-chemical" demand, there is need for further confirmation on this point and for the present, at least, it probably is better to assume that the value of ($\theta$) or of ($\mu$) is about the same in both cases.

*Laboratory Measurement of Bio-Chemical Oxidation.*—Under laboratory conditions, the measurement of natural bio-chemical oxidation is a definite and comparatively simple procedure, involving merely the incubation, under standard conditions of time and temperature of sealed samples of a polluted water containing an adequate supply of dissolved oxygen and noting the amount of oxygen absorbed by the sample in a given time. By applying relations (1), (2) and (4), the corresponding amount of oxidation, expressed in terms of oxygen absorbed, can be readily estimated for any other temperature within the ordinary seasonal range in natural bodies of water and for any other time within the first stage of oxidation at that temperature. As noted by Hoskins [14] in a recent paper, this calculation often may be made more conveniently by first transforming relation (1) to show the total amount of bio-chemical oxygen demand (B.O.D.) satisfied up to any given time, which Theriault [3] has expressed by the formula:

$$X_t = L(1 - 10^{-kt}) \qquad (5)$$

in which ($X_t$) denotes the B.O.D. oxidized up to time ($t$) and ($L$) the initial total B.O.D.* This relation is derived from (1) by noting that

* See previous footnote, page 253.

$$X_t = L - L_t = L - L \cdot 10^{-Kt} = L(1 - 10^{-Kt})$$

In Table 1 are given values of the first-stage oxidation constant ($k$) at different temperatures, ranging from intervals of 0.1° C. from 0° to 30° C., by applying formula (3). The value of ($L$) may be corrected to a

TABLE I.—*Value of Deoxygenation Coefficient (k) at Temperatures ranging Up to 30° C.*
(Calculated from formula: $k_{T^\circ} = k_{20^\circ}\ (1.047^{T-20})$

| Temp. ° C. | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0.0399 | .0402 | .0404 | .0406 | .0408 | .0409 | .0410 | .0412 | .0414 | .0416 |
| 1 | .0418 | .0420 | .0422 | .0424 | .0426 | .0428 | .0430 | .0432 | .0434 | .0436 |
| 2 | .0437 | .0439 | .0442 | .0444 | .0447 | .0449 | .0451 | .0453 | .0454 | .0456 |
| 3 | .0458 | .0460 | .0463 | .0465 | .0468 | .0470 | .0472 | .0474 | .0476 | .0478 |
| 4 | .0480 | .0482 | .0484 | .0486 | .0488 | .0490 | .0492 | .0495 | .0497 | .0500 |
| 5 | .0502 | .0504 | .0507 | .0509 | .0512 | .0514 | .0516 | .0519 | .0521 | .0524 |
| 6 | .0526 | .0528 | .0531 | .0533 | .0536 | .0538 | .0540 | .0543 | .0545 | .0548 |
| 7 | .0550 | .0553 | .0555 | .0558 | .0560 | .0563 | .0566 | .0568 | .0571 | .0573 |
| 8 | .0576 | .0579 | .0581 | .0584 | .0587 | .0589 | .0592 | .0595 | .0598 | .0600 |
| 9 | .0603 | .0606 | .0609 | .0612 | .0615 | .0617 | .0620 | .0623 | .0626 | .0629 |
| 10 | .0632 | .0635 | .0638 | .0641 | .0644 | .0646 | .0649 | .0652 | .0655 | .0658 |
| 11 | .0661 | .0664 | .0667 | .0671 | .0674 | .0677 | .0680 | .0683 | .0687 | .0690 |
| 12 | .0693 | .0696 | .0699 | .0703 | .0706 | .0709 | .0712 | .0715 | .0719 | .0722 |
| 13 | .0725 | .0728 | .0732 | .0736 | .0739 | .0742 | .0745 | .0749 | .0752 | .0756 |
| 14 | .0759 | .0763 | .0766 | .0770 | .0773 | .0777 | .0781 | .0784 | .0788 | .0791 |
| 15 | .0795 | .0799 | .0802 | .0806 | .0810 | .0813 | .0817 | .0821 | .0824 | .0828 |
| 16 | .0832 | .0836 | .0840 | .0844 | .0848 | .0852 | .0855 | .0859 | .0863 | .0867 |
| 17 | .0871 | .0875 | .0879 | .0883 | .0887 | .0891 | .0896 | .0900 | .0904 | .0908 |
| 18 | .0912 | .0916 | .0921 | .0925 | .0929 | .0934 | .0938 | .0942 | .0946 | .0951 |
| 19 | .0955 | .0959 | .0964 | .0969 | .0973 | .0977 | .0982 | .0987 | .0991 | .0996 |
| 20 | .1000 | .1005 | .1009 | .1014 | .1019 | .1024 | .1028 | .1033 | .1038 | .1042 |
| 21 | .1047 | .1052 | .1057 | .1062 | .1067 | .1071 | .1076 | .1081 | .1086 | .1091 |
| 22 | .1096 | .1101 | .1106 | .1112 | .1117 | .1122 | .1127 | .1132 | .1138 | .1143 |
| 23 | .1148 | .1153 | .1158 | .1164 | .1169 | .1174 | .1179 | .1184 | .1190 | .1196 |
| 24 | .1202 | .1208 | .1213 | .1219 | .1224 | .1230 | .1236 | .1241 | .1247 | .1252 |
| 25 | .1258 | .1264 | .1270 | .1276 | .1282 | .1288 | .1294 | .1299 | .1305 | .1311 |
| 26 | .1317 | .1323 | .1329 | .1336 | .1342 | .1348 | .1354 | .1360 | .1367 | .1373 |
| 27 | .1379 | .1385 | .1392 | .1398 | .1405 | .1411 | .1418 | .1424 | .1431 | .1437 |
| 28 | .1444 | .1451 | .1458 | .1464 | .1471 | .1478 | .1485 | .1492 | .1498 | .1505 |
| 29 | .1512 | .1519 | .1526 | .1533 | .1540 | .1547 | .1555 | .1562 | .1569 | .1576 |
| 30 | .1583 | | | | | | | | | |

given temperature by Theriault's equation (4). Hoskins has given in connection with his paper,[14] a conversion table for computing the value of ($X_t$) for various times up to 20 days at 20° C. It also may be calculated from equation (5) by using a table of logarithms or a " log log " slide rule. In Figure 1, is illustrated a series of curves showing values

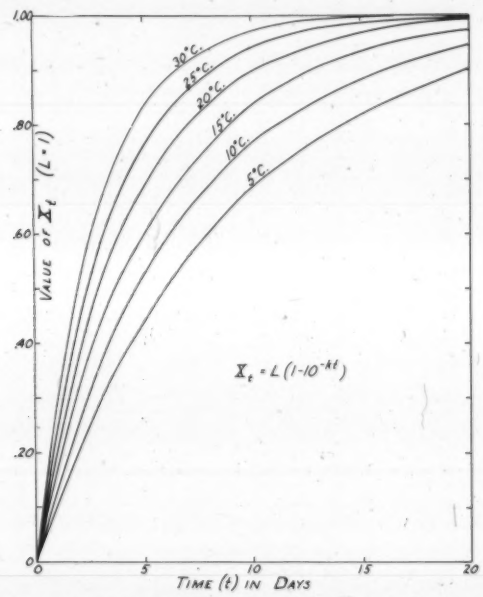


FIG. 1. Values of $(X_t)$ in equation (5) at various temperatures up to 30° C. and for times up to 20 days.

of $(X_t)$ at various times up to 20 days and at temperature intervals of 5° C. up to 30° C.

The definiteness and consistency with which progressive oxidation can be measured in a sealed laboratory sample of polluted water is due to the fact that throughout the period of observation, neither the concentration of oxidizable matter nor that of the dissolved oxygen undergoes any change except that which is due to oxidation. Under these conditions, it is possible to measure directly the extent of oxidation which has taken place in a given interval of time, either from the observed reduction in the D.O. content of the sample during the same time, or from the observed decrease in B.O.D. during that time.

*Bio-Chemical Oxidation Under Natural Conditions.*—In natural streams, however, this ideal situation never is fully realized, as the concentration of oxidizable matter is subject to very considerable changes due to physical influences, such as inflow (dilution or pollution), sedi-

mentation or scour, and adsorption of suspended organic matter by growths attached to the channel carpet. The concentration of dissolved oxygen likewise undergoes continual change through atmospheric reaeration and, occasionally through biological photo-synthesis by oxygen-producing plants. In sections of highly polluted streams where the flow is sluggish, the deoxygenating effects of sludge deposits are a further complicating factor, extremely difficult to evaluate, as these deposits are progressively cumulative under conditions of sedimentation and at the same time are being constantly oxidized; moreover, this process is subject to occasional interruption by freshets, which tend to scour or flush out all or a portion of the accumulated deposit. The difficulty of estimating the effect of sludge deposits is further enhanced by the fact that ordinary samples of the stream water include only the supernatant portion; hence neither the extent nor the rate of oxygen demand exerted by these deposits can be determined directly from an examination of such samples.

It thus appears that the true rate of oxidation in a polluted natural stream cannot ordinarily be directly ascertained either from the measured rate of decrease in the B.O.D. of the stream water, or from its observed rate of change in D.O. content, unless the former can be properly corrected for the combined effect of inflow, sedimentation and other disturbing factors and the latter, for the effect of reaeration.

In addition to the four agencies above noted, which directly affect the concentration of oxidizable matter in the stream, two others may further modify the trend of observed changes in B.O.D. One of these is the presence of material having an "immediate" oxygen demand, which tends to increase the composite rate of deoxygenation in the stream. The other is the occurrence of a transition from first-stage to second-stage oxidation between two sampling points, which may cause an apparent increase in B.O.D. between these points, or a decrease less than otherwise would be noted. Let us consider first the effects exerted by the four physical agencies above enumerated.

*Effect of Inflow.*—Inflowing drainage water may cause an increase or a decrease in the B.O.D. of the main stream, according to whether the tributary, or other source of inflow, is more or less polluted from this standpoint than is the main stream. In some instances, as noted recently by Hoskins and Butterfield,[15] dilution by a tributary may result in an increase rather than a decrease in the observed B.O.D. of the main stream water.

A definite relation appears to exist between the run-off from tributary drainage areas and the total B.O.D. contributed by such areas, as is illustrated in Figure 2, which has been plotted from data obtained by the Public Health Service in 1921-22.[7] In the Fox River watershed, the daily quantities of B.O.D. in pounds per square mile, are thus shown to

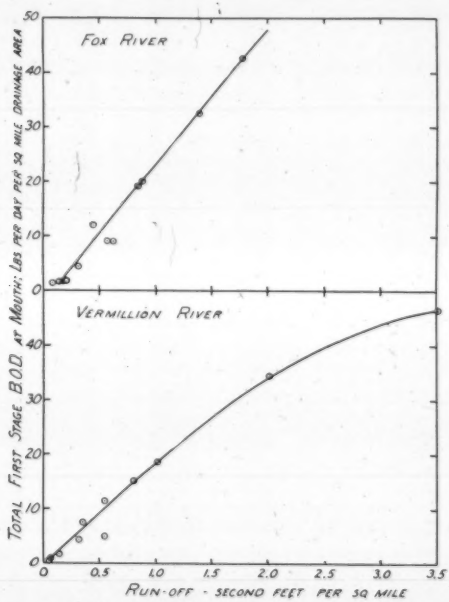


FIG. 2. Relation between rates of run-off and of biochemical oxygen demand discharged from the Fox and Vermillion river drainage areas.

have been almost directly proportional to the amount of run-off. From relationship plots of the same kind, drawn from similar data for each main tributary drainage area, a close approximation may be made to the total B.O.D. added to the main stream between any two sampling points, by noting the total intermediate drainage area and its run-off into the river between these points and assuming that the B.O.D. thus contributed would be the same per square mile as from the nearest main tributary area with the same run-off. In many cases this tributary area will constitute the larger portion of the total intermediate drainage area itself.

In correcting observed changes in B.O.D. of a main stream for the effects of inflow, whether dilution or pollution, allowance should be made for oxidation of any material brought into the stream at known points between their point of discharge and the next sampling station downstream at which the main stream B.O.D. is observed. In making such

allowance, it may be assumed that the inflowing B.O.D. is oxidized in the main stream at the same rate as is the B.O.D. of the main stream itself. To illustrate the result of such a correction, Figure 3 has been drawn from average observations made by the Sanitary District of Chicago in the upper portion of the Illinois River during a 6-year period, 1926–31. For access to these data, and other data from the same survey, and for per-

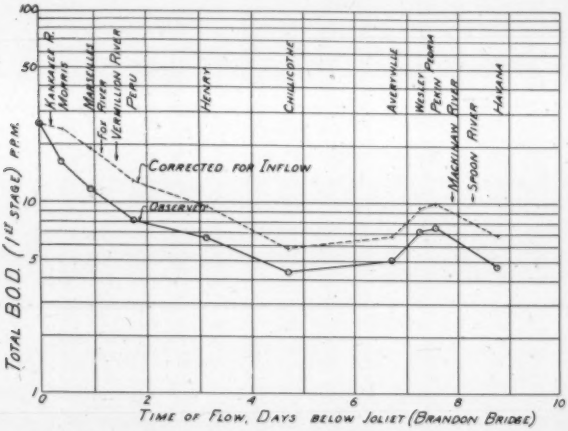


FIG. 3. Progressive changes in average first-stage biochemical oxygen demand observed in the upper section of the Illinois River, both as observed and as corrected for the effect of inflow. (Based on data collected by the Sanitary District of Chicago.)

mission to cite them in connection with this paper, grateful acknowledgment is made to Chief Engineer Philip Harrington, Sanitary Engineer Langdon Pearse and Chief Chemist F. W. Mohlman of the Sanitary District's staff.

*Effects of Sedimentation and Adsorption.*—Inasmuch as sedimentation and adsorption have the same effect in removing suspended oxidizable matter from the stream proper, they may be considered together, though it should be noted that adsorption probably occurs more largely in river stretches where attached growths of plankton are abundant, but where flow conditions are not ordinarily favorable to sedimentation. Both of these actions, however, result in storing oxidizable matter on the channel floor; hence they may be regarded as essentially similar phenomena.

The sedimentation or adsorption of suspended oxidizable material from the stream proper, or its predominance over scouring action, is

usually reflected by an observed rate of decrease in the B.O.D. of the stream water greater than can be accounted for as normal bio-chemical oxidation, after correcting for inflow and making due allowance for the rapid oxidation of any "immediate" oxygen demand which may be present in the stream.* By "normal bio-chemical oxidation" is meant oxidation at substantially the same specific rate as that which has been established by Phelps [2] and by Theriault [3] under laboratory conditions, corrected to the stream temperature by formula (2)..

If, for example, $(L_A)$ denote the observed B.O.D. of the river water at an upper station $A$ and $(L_B)$ the corresponding observed B.O.D. at a lower station $B$ (the latter corrected as above noted), the progressive removal of suspended oxidizable material from the stream proper by sedimentation or by adsorption would be indicated if $(L_A)$ were greater than the quantity $(L_B \cdot 10^{kt})$,† the latter representing a B.O.D. at Station $A$, which, if satisfied at the normal rate, would leave the observed residual $(L_B)$ at Station $B$. The numerical difference $(L_A - L_B \cdot 10^{kt})$ between these two quantities should be a measure of the rate at which such oxidizable material is being deposited from the stream.‡

The validity of this reasoning depends on the important question of whether the rate of oxidation of organic matters originating in sewage and other similar wastes is substantially the same in a polluted natural stream as it is under laboratory conditions of the ordinary B.O.D. test. Although it has been extremely difficult to obtain conclusive data bearing on this point, because of the rarity with which undistributed oxidation can be observed in natural streams, evidence has been cited by Streeter and Phelps [5] and elsewhere by Streeter [11, 16] pointing to a general consistency between these two rates. At a later point in this paper, further confirmatory evidence on this question, probably more direct and convincing than any heretofore advanced, will be given in connection with the results of an analysis made by the writer of a series of two-stage oxidation curves based on a large number of 40-day incubation tests made by the Sanitary District of Chicago on samples of Illinois River water collected at different points throughout its course. In view of this and the other evidence above noted, it appears at this writing reasonably safe to assume that in the stream proper, at least, bio-chemical oxidation of sewage matters proceeds at practically the same rate as under laboratory test conditions.

* A method for making such allowance will be discussed at a later point in this paper.

† The sign of $(kt)$ is positive in this latter case because the time $(t)$ is measured upstream from station $B$ and hence in a direction negative with respect to the flow of the stream.

‡ In the original report of their Ohio River study,[5] Streeter and Phelps followed this same concept in deriving an expression for an initial B.O.D. at Station $A$ based on average conditions between Stations $A$ and $B$.

Where sedimentation results in the accumulation of sludge deposits, the problem of evaluating the total deoxygenating effect of these deposits is complicated by the fact that throughout the process of deposition a portion, at least, of the sludge deposit is undergoing bacterial decomposition, possibly aerobic at the surface and anaerobic in the deeper strata, and the products of such decomposition are oxidized progressively at a composite rate probably depending on several factors, such as temperature, relative depth and age of the deposit and the extent to which various portions of the deposit are undergoing active fermentation.

The most direct clue as to the order of magnitude of this composite rate under conditions approaching those of natural streams is afforded by the results of some recent observations by Theriault and McNamee,[13] to which previous reference has been made in this paper. In connection with their observations of the rate of oxidation of sewage sludge in a laboratory aerating device designed by them, they also measured the rate of oxidation of a sludge deposit in an artificial channel through which streams of sewage and polluted river water were allowed to flow for various periods of time. From the results obtained, they concluded that under aerobic conditions in the laboratory, the oxidation of sludge proceeded substantially at the normal bio-chemical rate such as would be represented by $k = 0.10$ at 20° C., and that under stream-flow conditions of the experimental channel, the actual rate of oxidation of aerated sludge deposited over a period of 21 days was not materially different from the corresponding rate as observed under laboratory conditions. On the basis of their results, it would be inferred that under aerobic conditions, at least, sludge deposits in natural streams would be oxidized biochemically at about the same rate as would the oxidizable matter remaining suspended in the stream proper, which as previously noted appears to follow very closely the normal laboratory biochemical rate.

Less direct and, therefore, less conclusive evidence bearing on this same question is afforded by the results of some recent experiments by Fair and Moore [17] on the rates of digestion of sewage sludge in artificial tanks, under conditions more largely anaerobic than aerobic. Their results have indicated that under the conditions of their experiments, the rate of sludge decomposition was approximately one-half the normal biochemical rate at the same temperature; hence, would be indicated very roughly by a value of ($k$) approximating 0.05 at 20° C. The results of these experiments, together with those of other observations cited recently by Rudolfs,[19] would suggest the possibility that under anaerobic conditions such as might prevail in the lower strata of sludge deposits in polluted natural streams, the rate of decomposition and subsequent oxidation of these deposits might be somewhat lower than it would be under strictly aerobic conditions, such as might exist at and near the surface of the same deposits.

In order to gather more direct evidence on these points, further observations are desirable under stream-flow conditions approaching those of natural channels, in which both aerobic and anaerobic conditions may exist in a sludge deposit and the effects of variations in the depth and relative age of the deposit can be studied. Experiments of this nature are now being conducted by the Public Health Service, with a view to throwing further light, if possible, on these more doubtful points.

If the specific rate of oxidation of a sludge deposit were definitely known, it would be readily possible to calculate, by means of a simple formula which will presently be described, the total amount of B.O.D. accumulated in the deposit during a given period of time, making due allowance for the rate of addition of B.O.D. to the deposit through sedimentation and the rate at which each increment thus added is oxidized after its deposition. From the total amount of B.O.D. added to the deposit during the same period of time, it would then be possible to calculate, by difference, the total amount oxidized in the deposit during that period.

In order to explain the method followed in this calculation and the derivation of the accumulation formula on which it is based, let us assume, as before, two sampling Stations $A$ and $B$, at which the observed mean B.O.D. of the river water during the period in question is $(L_A)$ and $(L_B)$, the latter having been corrected for the effects of intermediate inflow and both quantities being expressed in terms of pounds per day.* Then $(L_A - L_B \cdot 10^{kt})$ † will measure, as previously indicated, the daily amount of B.O.D. removed from the stream proper by sedimentation and adsorption. Let us denote this quantity by the symbol $(p_s)$, so that

$$p_s = L_A - L_B \cdot 10^{kt} \text{ lbs. per day}$$

in which $(k)$ denotes the specific rate constant of normal biochemical oxidation in the stream proper, corrected to the stream temperature, and $(t)$ the time of flow from $A$ to $B$.

The quantity $(p_s)$ will include a certain portion of sludge B.O.D. oxidized in the stream proper, during the process of deposition, only the remaining unoxidized portion actually being added to the deposit. To approximate its amount, we may assume that the B.O.D. deposited settles at a uniform rate, so that its average concentration between points $A$ and $B$ may be represented by an amount equivalent to $\frac{1}{2}p_s$. Then if $(X_s)$ denote the amount of sludge B.O.D. thus oxidized during settlement, we may write that

* Obtained by the simple relation:

Lbs. per day = parts per million × discharge (c.f.s.) × 5.4.

† Note that $(kt)$ has a positive sign, for the reason previously explained.

$$X_s = 0.5p_s(1 - 10^{-kt}) \text{ lbs. in time } (t)$$

or

$$X_s = 0.5p_s(1 - 10^{-k}) \text{ lbs. per day} \tag{7}$$

If we now denote as $(p_d)$ the amount of B.O.D. actually added to the sludge deposit, we have that

$$\begin{aligned} p_d &= p_s - 0.5p_s(1 - 10^{-k}) \\ &= 0.5p_s(1 + 10^{-k}) \text{ lbs. per day} \end{aligned} \tag{8}$$

In equations (7) and (8) the time factor $(t)$ does not appear because the B.O.D. deposited is expressed in pounds per day and the settlement period considered is, therefore, one day, or unity.

With values of $(k)$ ranging from about 0.040 at a temperature slightly above 0° C., to 0.158 at 30° C., as shown in Table I, the corresponding percentage of $(p_s)$ oxidized per day during settlement would range from 4 percent at the lower temperature to 15 percent at 30°C., the difference being due to the effect of higher stream oxidation rates with increasing temperatures. Although this percentage would appear to be negligibly small at stream temperatures approaching the lower limit of this range, they might be significantly large at the higher temperatures corresponding to those of summer; hence, it hardly could be disregarded under the latter conditions, particularly if $(p_s)$ were relatively high.

If $(p_d)$ thus be taken as representing the pounds per day of B.O.D. actually added to the sludge deposit between points $A$ and $B$, we may then formulate the cumulative unoxidized B.O.D. of these daily increments to the sludge deposit, assuming a rate of oxidation of the sludge deposit as given by a constant $(K')$ and a total period of accumulation denoted by $(t')$ to distinguish it from the time of flow $(t)$.

If $(y)$ denote the amount of each daily increment $(p_d)$ remaining after $(t')$ days and $(L_d)$ the total cumulative B.O.D. in the deposit at time $(t')$, we may write that

$$y = p_d \cdot e^{-K't'}$$

and that

$$\begin{aligned} L_d &= \int_0^{t'} y\,dt' = \int_0^{t'} p_d e^{-K't'}\,dt' \\ &= -\frac{p_d}{K'} e^{-K't'}\Big|_0^{t'} = \frac{p_d}{K'}(1 - e^{-K't'}) \end{aligned}$$

or

$$L_d = \frac{p_d}{2.3k'}(1 - 10^{-k't'}) \tag{9}$$

where $k' = 0.434K'$.

As the total amount of B.O.D. added to the deposit during $(t')$ days is equivalent to $p_d t'$, then if we denote as $(X_d)$ the total amount of sludge

B.O.D. oxidized in the deposit during period ($t'$), we have that

$$X_d = p_d t' - L_d = p_d t' - \frac{p_d}{2.3k'}(1 - 10^{-k't'}) \qquad (10)$$

In Figure 4 are shown illustrative plots of the cumulative sludge

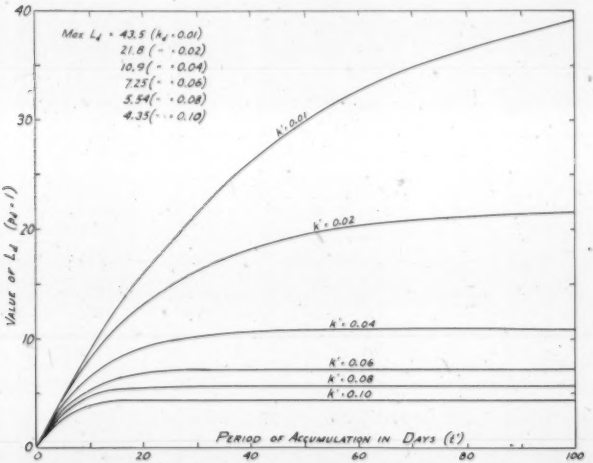


FIG. 4. Cumulative amounts ($L_d$) of sludge B.O.D. up to various times, as calculated from Equation (9) with different assumed values of the oxidation rate constant ($k'$), and with the rate of accumulation ($p_d$) assumed as equal to unity.

B.O.D. ($L_d$) with different assumed values of ($k'$) and during various periods of accumulation, the value of ($p_d$) being assumed as unity. Each curve, it will be noted, tends to approach an asymptote represented by the simple fraction, $p_d/2.3k'$, which is the limit of the function, $(p_d/2.3k')(1 - 10^{-k't'})$, when the accumulation period ($t'$) is prolonged indefinitely. The time required for ($L_d$) to practically reach its maximum is shown to vary from about 15 days with k' = 0.10 to 100 days or more with $k' = 0.02$. It also is noted, that the total amount of unoxidized B.O.D. accumulated in the sludge deposit up to any given time is greater with lower values of ($k'$), or lower rates of oxidation in the deposit.

The practical significance of these curves appears to be that during the early stages of sludge accumulation the amount of B.O.D. oxidized each day is less than the daily amount added, but that after a sufficiently long period of time has elapsed, a state of balance is approached whereby

the amount of B.O.D. added to the deposit each day is substantially equal to the daily amount of B.O.D. oxidized. After this point has been reached, the actual rate of sludge oxidation, in pounds per day, is, therefore, measured by $(p_d)$, the corresponding rate of addition to the deposit.

In Figure 5, giving a parallel series of plots of $(X_d)$, the cumulative

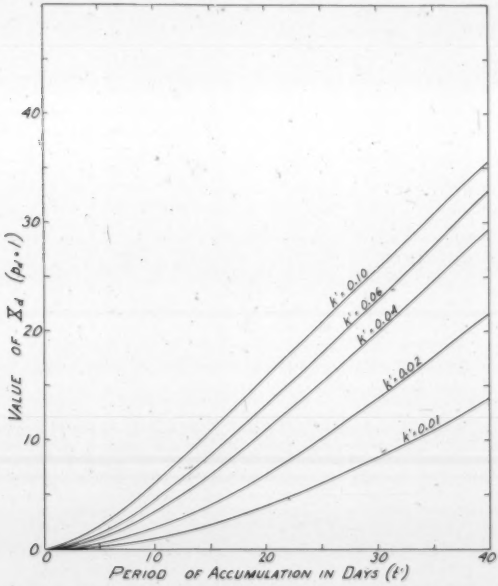


FIG. 5. Total amounts $(X_d)$ of sludge B.O.D. oxidized up to various times, as calculated from Equation (10), with values of $(L)$ corresponding to those illustrated in Figure 4.

amount of sludge B.O.D. oxidized after various periods of time, the effect of this state of balance is shown by the tendency of the plots to assume straight-line trends, parallel to each other and each having a slope of $p_d/t'$, so that for each unit of time (*i.e.*, $t' = 1$ day), the increase in $(X_d)$ is substantially equal to $(p_d)$.

From these considerations, the further practical conclusion may be drawn that where the period of sludge accumulation is relatively long, so that the rate of oxidation becomes substantially equal to the rate of

B.O.D. addition, the total rate of oxidation in a given stretch of a river, including that of the stream proper, the settling sludge and the deposited sludge, should approach very closely the observed rate of decrease in average B.O.D. between the upper and lower terminals of the stretch, (*i.e.*, $L_A - L_B$), the latter being first corrected for the effects of intermediate inflow. In the following illustrative example, based on actual observations, the period of accumulation considered is sufficiently long to fall within this category.

For the purpose of this example, reference may be made to the results of a laboratory survey of the Illinois River by the Public Health Service in 1921–22, a full report of which has been noted elsewhere [7] in this paper. From these results, the following represent yearly averages of observations made at two sampling points in the Illinois, the upper one (Station 286) being located immediately below Joliet and the lower (Station 240) at Ottawa, some 46 miles downstream. In this section of the river a considerable amount of sedimentation and adsorption of suspended oxidizable matter, originating chiefly in Chicago sewage, normally occurred during the period of the observations.

In the calculation which follows, the specific rate of oxidation of the sludge deposit has been assumed as being the same as in the overlying stream.

| | Illinois River at: | |
|---|---|---|
| | Sta. 286 (Joliet) | Sta. 240 (Ottawa) |
| Base Data: | | |
| Obs'd tot. 1st-stage B.O.D.: ($M\#/dy$ = Thous. lbs. per day) | $L_A = 1144$ | $L_B = 955$ ($M\#/dy$) |
| Corrected for inflow | | $L_{B'} = 854$ ($M\#/dy$) |
| Mean River Temperature ($T$) | | $= 11.9°$ C. |
| Value of ($k$) for river water | | $= 0.069$ |
| Value of ($k'$) for sludge deposit | | $= 0.069$ (assumed) |
| Mean time of flow ($t$) | | $= 1.05$ days |
| Total period of sludge accumulation ($t'$) | | $= 365$ days |
| Calculation: | | |
| $L_A$ | | $= 1144$ $M\#/dy.$ |
| $L_{B'} \cdot 10^{kt} = 854 \times 1.182$ | | $= 1009$ " |
| Difference ($p_s$) | | $= 135$ " |
| Oxidized in suspension: $\frac{1}{2}p_s(1 - 10^{-k})$ | | $= 10$ " |
| Added to sludge deposit ($p_d$) | | $= 125$ " |

From relation (9), we have:

$$\text{Total cumulative B.O.D. of Deposit } (L_d) = \frac{p_d}{2.3k'}(1 - 10^{-k't'})$$

$$= \frac{125}{2.3 \times .069}(1 - 10^{-.069 \times 365})$$

$$= \frac{125}{2.3 \times .069} \times .999 = 786 \text{ M}\#$$

From relation (10):

Total sludge B.O.D. oxidized ($X_d$) = $(125 \times 365) - 786$
= $45625 - 786 = 44839$ M#
$44839 \div 365 = 123$ M#/dy.

| | |
|---|---|
| B.O.D. oxidized in stream proper: | |
| (1) non-deposited: 1009 − 854 | = 155 " |
| (2) deposited in suspension: | = 10 " |
| Total B.O.D. oxidized | = 288 " |
| Observed decrease in B.O.D., corrected for inflow: ($L_A - L_B'$) | = 290 " |

From the results of this calculation it is noted that about 43 per cent of the total oxygen demand was exerted by the sludge deposit and 57 per cent by the overlying stream, and that the total exerted demand thus calculated, 288 thousand lbs. per day, approaches very closely the corrected observed decrease in total B.O.D. between the two points, 290 thousand lbs. per day. This serves to illustrate the previous statement that where long observational periods are considered, with correspondingly long periods of sludge accumulation, the average daily amount of sludge B.O.D. oxidized tends to approach closely the daily amount added to the deposit as shown by ($p_d$), and the total amount of B.O.D. oxidized tends to approximate closely the total observed decrease in B.O.D. between the two sampling points when corrected for intermediate inflow. For shorter periods of observation, as for individual months, a somewhat greater divergence would be noted in these two respects, as will be shown in connection with a later paper.

*Effect of "Immediate" Oxygen Demand.*—From the work of Theriault and McNamee previously noted [13] in this report, it is possible to estimate roughly the effect which the presence of an "immediate" oxygen demand in a stream concurrently with the usual biochemical demand, might be expected to exert on the composite rate of oxidation. Let us represent the biochemical rate of oxidation by the constant ($k_b$) and the corresponding "immediate" rate by the constant ($k_i$). In the form indicated by Theriault and McNamee, the course of oxidation would be represented by the relation:

$$X_t = L_b(1 - 10^{-k_b t}) + L_i(1 - 10^{-k_i t}) \qquad (11)$$

in which ($X_t$) denotes the total oxygen demand satisfied up to any time ($t$) and ($L_b$) and ($L_i$), the total initial biochemical and "immediate" oxygen demands, respectively.

If a sample of river water were incubated at 20° C., the value of ($k_b$) should approximate 0.1 and that of ($k_i$) about 1.6, with time ($t$) measured

in days. At a temperature other than 20° C., the values of ($k_b$) and ($k_i$) would be related to their 20° C. values according to formula (2), with ($\theta$) assumed in each case as being equal to 1.047, or with the heat of activation constant ($\mu$) as given in formula (3) assumed as approximating 8000.

At a laboratory incubation temperature of 20° C., about 97.5 per cent of the total " immediate " oxygen demand should be satisfied during the first 24 hours. If an incubation test of the stream water were made at this temperature and the 1-day and 5-day oxygen demand measured on the same sample, the amount of " immediate " oxygen demand should be roughly shown by the difference between the 1-day demand as measured and that which would be calculated from the observed 5-day result by multiplying it by the ratio, 0.206/0.684, or 0.3 approximately.

For the purpose of illustration, let us assume that the observed 5-day oxygen demand of a given sample of river water were 10.0 p.p.m., and that the corresponding 1-day demand were 4.0 p.p.m. If no immediate oxygen demand were present, this latter figure should be $(0.206 \div 0.684)10.0 = 3.0$ p.p.m.; hence their difference, 1.0 p.p.m., should indicate a first approximation of the immediate oxygen demand. But as this is also included in the 5-day demand as observed, we would assume tentatively that the 5-day biochemical demand was 9.0 p.p.m. If we recalculate the 1-day biochemical demand on this basis, we obtain 2.7 p.p.m. The difference between this figure and the 4.0 p.p.m. observed would be 1.3 p.p.m. as a second approximation of the immediate demand. By repeating this process of calculation a third time, we obtain a result of 1.4 p.p.m. which is not altered, within 0.1 p.p.m., by a fourth repetition. We thus may conclude from this trial-and-error computation that the immediate oxygen demand of the sample approximates 1.4 p.p.m. and the 5-day biochemical demand, 8.6 p.p.m. From the latter figure we may estimate that the total first-stage total B.O.D. would be $8.6 \div 0.684 = 12.5$ p.p.m. at 20° C.

From the results of this calculation we may estimate roughly the reduction in total oxygen demand, including the " immediate " demand, which would be expected to occur in the river during any given time of flow, applying equation (11). Let us assume, for the sake of simplicity, that this time of flow is 2 days and the stream temperature 20° C. Then we have that

$$\begin{aligned} X_t &= 12.5(1 - 10^{-0.1\times 2}) + 1.4(1 - 10^{-1.6\times 2}) \\ &= 12.5 \times 0.369 + 1.4 \times 0.9995 \\ &= 4.6 + 1.4 = 6.0 \text{ p.p.m.} \end{aligned}$$

Of this total demand satisfied, 4.6 p.p.m. would represent that which has been oxidized biochemically, if it be assumed that all of the 12.5

p.p.m. of true B.O.D. initially present remained in the supernatant stream. On this basis we would expect that $12.5 - 4.6 = 7.9$ p.p.m. of B.O.D. would remain in the stream after 2 days flow at 20° C. If, however, the observed B.O.D. should be lower than 7.9 p.p.m. at the 2-day point, after correcting for the effect of inflow, we would conclude that some of the oxidizable matter had been withdrawn from the stream proper through sedimentation and adsorption and the amount of material thus removed could be estimated by projecting the B.O.D. observed at the lower point back to the initial station 2 days flow upstream, and subtracting the result from 12.5 p.p.m. Thus if the observed B.O.D. at the lower point were 6.0 p.p.m. this would represent a residual from $6.0 \times 10^{0.1 \times 2}$, or 9.5 p.p.m. at the initial station, and the total B.O.D. removed by sedimentation would be calculated as being $12.5 - 9.5 = 3.0$ p.p.m.

In addition to the "immediate" oxygen demand brought into a given river stretch by the stream proper, is that which may originate in the local sludge deposit. Although little definite information exists at the present writing as to the extent of this kind of oxygen demand liberated by ordinary sludge deposits, it may constitute, in some cases, an important element in the total oxygen demand exerted by deposits of any considerable depth, and likewise by gas-lifted sections of these deposits.

Wherever B.O.D. tests of the stream water at the lower terminal of a particular river stretch indicate the presence of an "immediate" oxygen demand in excess of that which can be accounted for as a residue of that which may be observed concurrently at the upper station, the total amount of "immediate" demand originating in the deposit may be estimated by applying equation (9). Let $(L_i')$ represent the excess of immediate oxygen demand observed at the lower station and $(p_i)$ the total immediate demand added to the stream from the sludge deposit, both being expressed either in concentration or as pounds per day. Then, if $(t)$ denote the time of flow of the stream through the stretch under consideration, and $(k_i)$ the rate constant for the "immediate" oxygen demand, as in equation (11), we may write:

$$L_i = \frac{p_i}{2.3k_i}(1 - 10^{-k_i t}) \tag{12}$$

whence

$$p_i = \frac{2.3k_i L_i}{1 - 10^{-k_i t}} \tag{13}$$

Inasmuch, however, as the rate at which "immediate" oxygen demand is satisfied is so rapid that at 20° C., about 97.5 per cent would be oxidized in 24 hours, the residual amount of such demand at the

lower terminal of a river stretch having a relatively long time of flow would be so small as to be hardly measurable. For example, if $(p_i)$ were assumed as 5.0 p.p.m. in the above equation, and $(k_i)$ as 1.6 at 20° C., the residual immediate demand with one day time of flow would be

$$L_i = \frac{5.0}{2.3 \times 1.6}(1 - 10^{-1.6 \times 1})$$
$$= 0.034 \text{ p.p.m.}$$

which is so small as to be negligible. In some instances, a fairly large immediate oxygen demand originating in local sludge deposits may thus have disappeared entirely by the time that the stream water has reached a lower observation point.

If further studies should justify an assumption that all, or practically all, of the oxidizable matter resulting from the progressive breaking down of sludge deposits in polluted streams may reach the overlying water in enzymic form, the deoxygenating effect of this material on the overlying stream could be estimated very readily by calculating first the value of $(X_d)$ in equation (10) and then substituting this value as $(p_i)$ in equation (12), with $(k_i)$ taken as 1.6 at 20° C. and varied according to temperature relationship (2) or (3). With the present very limited knowledge of this phase of the subject, such an assumption would hardly seem justified, however, and unless some definite laboratory evidence of the presence of an immediate oxygen demand in the stream water were available, it probably would be safer to assume that the total oxygen demand oxidized from a sludge deposit is equivalent to that which is oxidized biochemically.

*Effect of Two-stage B.O.D.*—In the introductory section of this paper, the laboratory observations of Adeney and of Theriault on the existence of two distinct stages of oxidation in sewage and polluted water have been noted. In this connection, Theriault has pointed out that where a transition from first-stage to second-stage oxidation occurs within the period of incubation of a sample of polluted water tested for B.O.D., the result obtained may be disproportionately high as compared with that which might be obtained from the same sample at an earlier phase of oxidation wholly within the first stage. If this principle were likewise applicable to progressive oxidation in a natural stream, it is conceivable that an apparent increase in 5-day B.O.D. might be observed in the stream water, otherwise unaccounted for, in a stretch where a transition from first to second stage oxidation took place.

It is of interest in this connection to note the results of an extensive series of tests made by the Sanitary District of Chicago during a period of four years, 1927–30, on multiple samples of water collected at various

points along the Illinois River and incubated for different periods up to 40 days at 20° C., the B.O.D. of each sample being measured over each period.*

From averages of these results for the entire four years, including summer and winter observations, a series of curves has been constructed, showing the course of oxidation in the river water at each collection point. In Figure 6 are shown plots of these several curves, each one

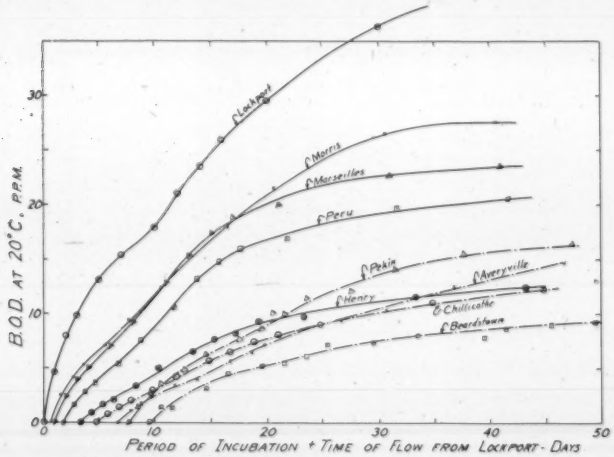


FIG. 6. Plots of average curves showing the course of oxidation in samples of Illinois River water collected at various points. (Based on data collected by the Sanitary District of Chicago, during the years 1927-30.)

being started at a time corresponding to the mean time of flow of the river from Lockport to the point of collection.

Considering the Lockport curve, it will be noted that a change in the inflection of this curve, marking the transition from first to second stage oxidation, occurs at about 10 days from the start, but considerably in advance of the time at which the first-stage portion of the curve, if extrapolated beyond 10 days, would approach its true asymptote, corre-

* For permission to refer to these data, acknowledgment is made to the Sanitary District officers previously noted in this paper.

† This scheme of plotting is the same as that which was followed by Mohlman, Edwards and Swope in their previous analysis of similar curves obtained from the same series of observations. (See Jour. Ind. and Eng. Chem., Vol. 19, p 242 et seq., March, 1928)

sponding to the total first-stage B.O.D. In passing downstream, successively to Morris, Marseilles, Peru, Henry and Chillicothe (the point last named being located about 112 miles and 4.8 days mean time of flow below Lockport), it is noted that the actual period of incubation up to the transition point of the curve is progressively shortened, but that the total time from Lockport to this transition point, including the period of incubation and the time of flow, remains about the same, that is, about 10 days. This observation probably constitutes the best and most direct evidence that the rate of biochemical oxidation in the stream proper approximates very closely the corresponding laboratory rate at the same temperature.

Passing further downstream, from Chillicothe to Pekin, the influence of pollution from the Peoria district is shown by the higher initial rise of the Pekin curve and by the prolongation of its first stage. If the Pekin curve be compared with that observed at Beardstown, 64 miles and about 2 days time of flow further downstream, the transition points of these two curves are again shown to be roughly synchronized with each other, each one being at about 19 days total time from Lockport as measured on the abscissa scale. In this case, as between Lockport and Chillicothe, no major pollution of the river occurs and the only important effect of intermediate inflow on the trend of the curves is that of dilution together with a certain amount of pollution from tributaries.

In order to facilitate a direct comparison of the curves illustrated in Figure 6, an effort has been made to formulate them in terms of the same kind of constants as those which define the normal first-stage oxidation curve. The following discontinuous equation has been found to give an excellent fitting of all of these curves, when only *positive* values of $(t - a)$ are considered:

$$Y = L_c(1 - 10^{-k_c t}) + L_n[1 - 10^{-k_n(t-a)}] \qquad (14)$$

where $(Y)$ denotes the total B.O.D. oxidized up to any time $(t)$, $(L_c)$ and $(L_n)$ the total first and second stage B.O.D.'s respectively, $(k_c)$ and $(k_n)$ the corresponding specific rates of oxidation, and $(a)$ a "lag" constant indicating the time at which second-stage oxidation begins.

For mutual comparison, values of these five constants derived for the Lockport, Morris, Marseilles, Peru and Henry curves in Figure 6 have been set down in Table II, as follows:

On referring to Table II, it will be noted that the specific rate of first-stage oxidation, as indicated by a value of $(k_c)$ averaging 0.103 (which incidentally is practically equal to the Phelps-Theriault 20° C. value, 0.100, for first-stage oxidation), is shown to be roughly three times the specific rate of second-stage oxidation, which is given by a value of $(k_n)$ averaging 0.031. It also will be noted that the total first- and second-

TABLE II.—*Values of Constants in Equation (14) Derived from Five Two-stage Oxidation Curves Illustrated in Figure 6*

(Based on average results of 40-day incubation tests of Illinois River water at 20° C. by Sanitary District of Chicago, years 1927–30, respectively)

| Sampling Point | Miles Below Lockport | $L_c$ (p.p.m.) | $L_n$ (p.p.m.) | $k_c$ | $k_n$ | (*a*) (Days) |
|---|---|---|---|---|---|---|
| Lockport | 0.0 | 20.5 | 20.5 | 0.090 | 0.031 | 11 |
| Morris | 27.8 | 10.2 | 18.5 | 0.100 | 0.030 | 7 |
| Marseilles | 43.8 | 9.8 | 15.0 | 0.115 | 0.030 | 5 |
| Peru | 68.7 | 7.9 | 13.0 | 0.100 | 0.035 | 6 |
| Henry | 95.1 | 4.8 | 7.7 | 0.100 | 0.030 | 5 |
| Mean | | | | 0.103 | 0.031 | |

stage B.O.D.'s as observed at Lockport were the same, 20.5 p.p.m. Below this point, the first-stage B.O.D. is shown to diminish more rapidly than the second-stage B.O.D., probably because of the higher rate of oxidation of the former and because oxidation of the latter doubtless lags considerably behind that of the former, in the stream as in the laboratory.

TABLE III.—*Comparison of Calculated and Observed Ordinates of Five 40-day B.O.D. Curves Illustrated in Figure 6*

(Calculated ordinates based on Constants given in Table 2)

| Time from Initial Point (*t*), in Days | Ordinate of Curve (B.O.D. Satisfied, p.p.m.) | | | | |
|---|---|---|---|---|---|
| | Lockport | Morris | Marseilles | Peru | Henry |
| 5—Calculated | 13.2 | 6.9 | 7.2 | 5.4 | 3.3 |
| Observed | 13.1 | 7.0 | 7.2 | 5.4 | 3.3 |
| 10—Calculated | 17.9 | 12.7 | 13.5 | 10.6 | 6.5 |
| Observed | 17.9 | 12.3 | 13.0 | 10.6 | 6.4 |
| 15—Calculated | 24.7 | 17.7 | 17.1 | 14.3 | 8.4 |
| Observed | 25.9 | 17.8 | 18.8 | 15.9 | 9.2 |
| 20—Calculated | 29.5 | 21.2 | 19.5 | 16.7 | 9.8 |
| Observed | 29.5 | 21.4 | 19.9 | 16.8 | 9.7 |
| 30—Calculated | 35.7 | 24.9 | 22.1 | 19.0 | 11.1 |
| Observed | 36.3 | 26.3 | 22.7 | 19.6 | 11.5 |
| 40—Calculated | 38.4 | 26.8 | 23.5 | 20.1 | 11.8 |
| Observed | 38.4 | 27.5 | 23.6 | 20.5 | 12.3 |

Utilizing these average values of ($k_c$) and ($k_n$) and also those of ($L_c$) and ($L_n$) as given in Table II, it is possible to estimate, by the method previously described, the proportion of the decrease in B.O.D. observed between Lockport and Henry (considering separately the first-stage and second-stage demands) which might be attributable to oxidation in the stream proper and to the combined effects of dilution, sedimentation and adsorption. As the mean time of flow between the two points approximated 3.3 days throughout the period of the tests, we may estimate that with first and second stage B.O.D.'s observed at Henry equivalent to 4.8 and 7.7 p.p.m., respectively, these demands represented residuals from oxidation in the stream proper of B.O.D.'s at Lockport equivalent to:

$$4.8 \times 10^{0.103 \times 3.3} = 10.3 \text{ p.p.m. (1st stage)}$$

and

$$7.7 \times 10^{0.031 \times 3.3} = 9.8 \text{ p.p.m. (2nd stage)}$$

The difference between these respective figures and the observed first- and second-stage B.O.D.'s at Lockport would represent the reduction due to the combined influences of dilution, sedimentation and adsorption. As the first and second stage B.O.D.'s observed at Lockport from these tests (Table II) were the same, that is, 20.5 p.p.m., these differences would be $20.5 - 10.3 = 10.2$ p.p.m. for the first-stage B.O.D. and $20.5 - 9.8 = 10.7$ p.p.m. for second-stage B.O.D. The practical agreement between these two differences, serves to confirm, in a broad sense, the expectation that these physical influences noted should exert about the same combined effect on the carbonaceous and the nitrogenous materials comprising the first and second-stage B.O.D.

An important practical question involved in the interpretation of the foregoing data is that of whether the progressive oxidation of the nitrogenous or second-stage B.O.D. in a bottom-sludge deposit would be expected to exert a deoxygenating effect on the overlying stream, as is the case with the oxidation of the carbonaceous, or first-stage oxygen demand. From such evidence as is available it seems very doubtful that second-stage oxidation would have such an effect under natural conditions of a stream, as the primary intermediate product of such oxidation is ammonia, which is, of course, readily soluble in water and presumably would be carried away by the stream before it could be oxidized to nitrite or nitrate, unless the stream itself were definitely in a state of nitrification. But nitrification does not ordinarily occur in portions of polluted streams subject to sludge deposition, which usually proceeds in zones more or less immediately downstream from major sources of pollution, where oxidation is in the first stage. This is clearly shown in the curves of Figure 6 for the upper sections of the Illinois River above Lockport, in which most of the active sludge deposition takes place. It is quite

possible, however, that the liberation of ammonia from portions of sludge deposits undergoing slow nitrification might have some influence on the course of second-stage oxidation in downstream zones far removed from immediate sources of pollution.

## Summary

As a basis for a later discussion of certain observational and experimental data bearing on rates of oxidation in natural streams polluted by sewage and certain types of industrial wastes, the various factors have been pointed out which modify observed progressive changes in the B.O.D. of polluted stream waters. Among these factors are intermediate inflow (pollution or dilution), sedimentation and adsorption, channel scouring, the presence of an "immediate" or "enzymic" oxygen demand and a transition from first-stage to second-stage oxidation in the stream proper.

In this connection it has been shown how corrections for the effect of these several factors may be applied to observed changes in the B.O.D. of the stream and how a rational method of calculating the deoxygenating effect of sludge deposits may be developed from observations of B.O.D. in the supernatant water. The simple formula developed yields results indicating that after a sufficiently long period of sludge accumulation, the rate of oxidation of the sludge deposit tends to approach very closely the rate of B.O.D. accumulation in the deposit. Where this condition prevails, the total rate of oxidation in the stream is measured very nearly by the observed change in B.O.D. between successive sampling points, when corrected for the effects of intermediate inflow.

A method is described for estimating from concurrent 1-day and 5-day B.O.D. tests of the stream water, the proportion of "immediate" oxygen demand in the water, and the practical application of this method is illustrated by an example.

From an analysis of graphs of two-stage B.O.D. curves obtained from the average results of an extensive series of 40-day B.O.D. tests made by the Sanitary District of Chicago at several points in the Illinois River, it is shown that the transition from first-stage to second-stage oxidation in samples of the river water tends to be advanced, in progressing downstream, roughly by the time of flow of the river between various sampling points. It also is shown, from a discontinuous equation fitting these curves, that at 20° C., the specific rate of the second, or nitrification, stage of oxidation is approximately one-third the rate of first-stage, or carbonaceous, oxidation, which tends to approach closely the laboratory value, 0.1, established by the work of Phelps and Theriault.

Aside from yielding a new constant, namely, that which defines the rate of second-stage oxidation in terms similar to those of the Phelps-

Theriault constant for first-stage oxidation, the results of analysis of these two-stage oxidation curves have contributed the best and most direct evidence which thus far has come to the writer's attention indicating that the rate of oxidation of sewage matters under natural stream conditions approaches closely the corresponding rate as measured under laboratory conditions of the ordinary incubation test for biochemical oxygen demand. If further evidence of the same kind should confirm this finding, a fact of primary importance in the accurate measurement of natural stream oxidation by the usual laboratory methods will have been firmly established.

In connection with this paper, three additional new constants have been discussed and the need existing for their more precise definition has been pointed out. These are: (1) a constant, or series of constants, defining the specific rate of oxidation of sewage sludge deposits in natural streams; (2) a temperature coefficient for this rate, for temperatures ranging up to the summer maxima for natural streams; and (3) a temperature coefficient for the rate of oxidation of "immediate" or "enzymic" oxygen demand, likewise for temperatures ranging up to the summer maxima for natural streams. A systematic effort is now being made at the Stream Pollution Investigations Station of the Public Health Service to determine values of the sludge deposit constant under experimental conditions approximating those of natural streams. It is possible also that from this series of experiments, now in progress, some data bearing on the temperature variations of this constant will be obtained, though in order to do so the observations now planned will have to be extended considerably in their scope. Although some preliminary data bearing on the temperature variations of the "immediate" oxygen demand constant have resulted from the work of Theriault and McNamee referred to in this paper,[13] these writers have noted the need existing for more elaborate and precise confirmatory evidence on this point.

The new method herein proposed for estimating the cumulative deoxygenating effect of sewage sludge deposits in natural streams, utilizing ordinary B.O.D. determinations in the stream water at two or more sampling points, can be shown, as above indicated, to yield total rates of deoxygenation for the entire stream section closely approaching, for long periods of time, those which are measured directly by the observed net rate of decrease in the total oxygen demand of the supernatant stream water. The length of this period will depend on the stream temperature and on the rate at which the sludge deposit is oxidized, being longer for lower stream temperatures and lower rates of sludge oxidation. For this reason, due caution should be exercised and account taken of these limitations in attempting to use the observed rate of

decrease in the oxygen demand of a stream water as a direct measure of the total rate of oxidation in the stream.

In the second part of this paper, the second major factor involved in natural stream oxidation, namely reaeration, which constitutes the source of oxygen by which the internal processes of stream oxidation are supported, will be discussed from a similarly basic viewpoint. In this connection practical methods will be described for measuring reaeration and for estimating the combined effects of this and the oxygen demand factor on the course of oxygen loss and recovery in sewage-polluted streams.

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# WATER POLLUTION STUDIES IN WISCONSIN

## EFFECTS OF INDUSTRIAL (PULP AND PAPER MILL) WASTES ON FISH

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### Introduction

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Stream pollution by industrial wastes has created numerous many-sided problems. One such problem involves determination of the causes for injury to or destruction of fish, and the development of ways and means demanded by the public for protection of fish life. In pollution abatement activities in Wisconsin questions are frequently asked as to the specific effects of certain wastes on fish and other aquatic life. The literature provides some information. For instance, it is fairly well known that pollution may detrimentally affect fish in any or all of the following ways: (1) by changing natural stream conditions, such as depleting the dissolved oxygen, so that the fish suffocate, or seek another habitat, either due to the oxygen deficiency or to the effect the wastes have on plants or lower animal life constituting fish food; (2) by direct poisoning or killing of fish by toxic substances, and (3) by interference with the development of fish life and young fish, that is, influence on the reproduction of the species. Much is yet to be learned, however, concerning the relative importance of these factors and the degree of tolerance of fish for various kinds of trade wastes. There is definite need for such knowledge in the development of waste utilization or treatment procedures intended to solve pollution problems involving protection of fish and fishing interests. Studies to meet this need in part have been carried out during recent years. The object of this report is to describe experiments conducted in Wisconsin to provide information concerning the effects of pulp and paper mill wastes on fish.

Experimental work described was undertaken as part of the general pollution control program of the State Committee on Water Pollution. The studies were conducted during the summer months of 1930, '31 and '32 by the temporary biologist of the Bureau of Sanitary Engineering, Wisconsin State Board of Health, which is the adminis-

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trative agency for the Committee on Water Pollution. Chemical analyses, other than control tests, were made by the State Laboratory of Hygiene, space and facilities for setting up fish tanks were furnished by the Hydraulic and Sanitary Engineering Department of the University of Wisconsin, and fish were obtained with the assistance of the Wisconsin Conservation Commission. Only through the interested cooperation of all concerned was it possible to carry out to best advantage the studies herewith reported.

Waste liquors from the sulphite and sulphate (kraft) processes of pulping wood were used in the experimental work. It has previously been shown that these wastes deplete the oxygen in streams, the sulphite wastes having a much higher oxygen demand than Kraft pulp mill wastes.[1] Depletion of the dissolved oxygen in a stream by these wastes will cause fish to migrate or die of suffocation. It was desired to ascertain: (1) whether in addition to their oxygen requirements, these wastes had direct toxic or poisonous effect; (2) whether the effluent from a recovery system proposed for utilizing certain constituents of sulphite waste liquor would remove such toxic effects as might be found to exist; and (3) whether treatment with ozone would reduce or eliminate any toxic effects occasioned by the wastes. The work also included a study of the influence of wood fiber or paper pulp in suspension in water on fish.

In brief, the results obtained indicate that the primary effect of sulphite and sulphate waste liquors on fish life is through removal of the dissolved oxygen from the water. While it was found that direct toxic effects on the game fish used in the experiments occur with both wastes in high concentrations, such concentrations would not be expected in streams below pulp mills in Wisconsin, except possibly in the immediate vicinity of sewer outlets. Fish died in short periods in 1 to 50 dilutions of sulphite waste liquor, but many survived the duration of the experiment (28 days) in a dilution of 1 to 200 without any serious ill effects. While dilutions of 1 to 500 of sulphate waste liquor were irritating to fish, definite toxic effects occurred mainly in dilutions of 1 to 200 or less. Death of fish is attributed to respiratory paralysis, caused in part presumably by mercaptans or sulphur compounds. Since these sulphite and sulphate wastes would probably deplete the dissolved oxygen in a stream below the critical amount necessary to sustain fish life before the above limiting dilutions for toxic effects are encountered, the most significant characteristic from the pollution point of view is their oxygen demand. Our present knowledge does not permit any statement concerning their relative effects on fish foods and reproduction of the species.

Oxygen demands of the waste were reduced by aeration, observa-

tions indicating that the toxicity of the sulphate liquor was also reduced. The toxicity of the effluent from the recovery process proposed for sulphite waste liquor was but slightly reduced as compared to the raw liquor, even though studies have indicated that at least a 75 per cent reduction in oxygen demand could be accomplished by the process. Ozone treatment of the wastes did not accomplish expected improvements, and from the results obtained and other considerations it appears that the process is of limited value in connection with securing practical solutions of pollution problems occasioned by sulphite and sulphate waste liquors.

Tests indicate that pulp fiber does not ordinarily accumulate in, and clog the gills of fish, causing death by suffocation. There is, however, the possibility that fibers and other solids will settle to the bed of a stream and decompose there, using up the dissolved oxygen necessary to support fish and other aquatic life.

The degree of tolerance of the species of fish included in the experiment to small amounts of dissolved oxygen has been more definitely established by the data obtained with the control tanks. The information further supports the selection of two parts per million of dissolved oxygen as the very minimum for sustaining fish life for general stream pollution control activities.[1]

## I. The Effects of Waste Sulphite Liquor on Fish

It is well recognized that waste sulphite liquor has a very high oxygen demand, and that when discharged into a stream, it will take up the oxygen dissolved in the water until its oxygen requirements are satisfied. Furthermore it is obvious that if this depleting process lowers the dissolved oxygen content of the water below the critical point, the fish life of the stream will die from suffocation. But aside from the effects due to lack of oxygen, does the sulphite liquor have a toxic influence on the animal life with which it may come in contact?

Reports on the effects of sulphite liquor on fish have been made by Knight ('01),[2] Marsh ('07),[3] Thomas ('19),[4] Sutter and Moore ('22),[5] Belding ('27),[6] and Nightingale and Loosanoff ('28).[7] These investigations indicate that the deleterious effects of waste sulphite liquor are due mainly, if not entirely, to the depletion of oxygen and that the problem of sulphite pollution may be effectively solved by satisfying the oxygen demand of the liquor at the expense of sources other than the dissolved oxygen of the water of the stream. Insofar as we are aware no attempt has been made to separate a possible toxic effect from one of oxygen depletion. The following experiments were designed to determine whether or not waste sulphite liquor had a toxic effect on fish which were subjected to its influence.

*Methods Employed.*—If fish were exposed to various dilutions of waste sulphite liquor which were continuously aerated to a point that a residue of dissolved oxygen was maintained over and above the immediate requirements of the liquor, then it would appear logical to assume, other factors being equal, that any abnormal condition appearing in these fish should be ascribed to a toxic effect of the sulphite liquor, and not to oxygen deficiency. To be conclusive, such experiments should be carefully guarded by controls of fish in (1) non-aerated dilutions of liquor, (2) aerated water, (3) non-aerated water.

Accordingly a series of metal tanks of 250 gallon capacity were set up in a sub-basement where the temperature was quite uniform. (See Figure 1.) The inner surfaces of the tanks were coated with paraffin

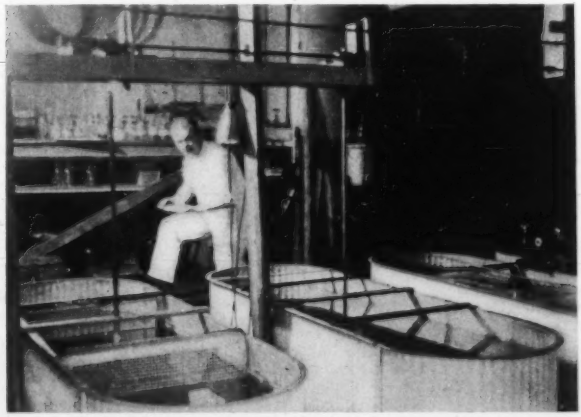

FIG. 1.—View of the laboratory where the fish experiments were conducted. The tanks in the foreground contain non-aerated dilutions which were mechanically stirred or agitated. In the background is the chemical table and the weighing tank.

to protect the metal from the corrosive action of the sulphite liquor. Compressed air, forced through basswood plugs, provided oxygen for the aerated dilutions and also maintained thorough mixing. (See Figure 2.) Mechanical stirrers kept conditions constant in the non-aerated tanks. The diluting water was from the lake from which the experimental fish were taken. Only hardy, mature fish were used. In any species the fish selected were of uniform size. The species included the yellow perch (*Perca flavescens*), the blue-gill (*Lepomis pallidus*), the

large mouth black bass (*Micropterus salmoides*) and a few others which were not available in sufficient numbers to be of any great value. All these fish are normal inhabitants of the rivers of Wisconsin into which pulp and paper mill wastes are being discharged. The sulphite liquor

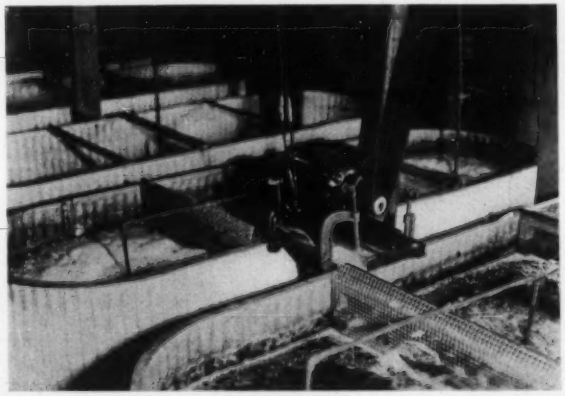

FIG. 2.—Another portion of the laboratory. The tanks in the foreground contain dilutions which are being aerated. Note the foam which is accumulating on the surface.

used was taken directly from a pulp mill digester, immediately before a blow-off period. It had a specific gravity of 1.048. Analyses of the sulphite waste liquor are given in Table I.

TABLE I.—*Analyses of Sulphite Waste Liquor Used in Fish Experiments*

| Determination | Sample Number * I | Sample Number * II |
|---|---|---|
| Total Solids | 99,060 p.p.m. | 127,730 p.p.m. |
| Loss on Ignition | 82,360 " | 115,330 " |
| Suspended Solids | 1,368 " | 152 " |
| Loss on Ignition of Suspended Solids | 372 " | 20 " |
| Oxygen Consumed | 66,000 " | 66,800 " |
| 5 Day Biochemical Oxygen Demand | 10,200 " | 11,600 " |
| Total Sulphur Dioxide | 0.77% | 0.60% |
| Free Sulphur Dioxide | 0.02% | 0.01% |
| Combined Sulphur Dioxide | 0.75% | 0.59% |

* Sample I—Collected from the side relief of a digester just before the end of the cook.
Sample II—Obtained from a cook using hemlock chips.

The dilutions used were 1 to 50, 1 to 100 and 1 to 200. These concentrations are considerably higher than will be found in any river below a sulphite pulp mill in Wisconsin, but it was believed that toxic effects, if any, would be more evident and appear much sooner than they would in weaker concentrations. The dissolved oxygen content (Theriault's modification of the Winkler method),[9] pH and temperature readings were made at least daily. The biochemical oxygen demand was determined three times a week. The behavior of all fish was carefully watched. The fish were examined frequently to determine their condition. Practically all fish were autopsied at death or were killed at the end of the experiment and examined for gross abnormalities.

*Results and Discussion.*—In the aerated control, the blue-gills and black bass lived the duration of the experiment (28 days). The perch lived, on the average, 11 days, but succumbed to infections of Saprolegnia. The pH varied from 8.1 to 7.8; the temperature from 23° to 19°; the dissolved oxygen content from 7.6 to 5.0 p.p.m. With the exception of the perch, all fish behaved in an apparently normal manner, took food regularly and at autopsy showed no gross abnormalities.

In the non-aerated control, the dissolved oxygen dropped rapidly, and most of the fish died with symptoms of oxygen hunger. With the decrease in the number of fish, the few remaining lived for several days. Some of the black bass lived for 19 days, having successfully withstood, for a period, a dissolved oxygen content of less than 0.8 p.p.m.

In the non-aerated sulphite dilutions, 1 to 50, 1 to 100, and 1 to 200, all fish quickly showed signs of oxygen hunger, swam at the surface, gulped air and died within a few hours. The length of life of the fish in the different dilutions varied with the concentration of the sulphite liquor. This would be expected, for the rate of oxygen consumption by the liquor varies directly with its concentration. At the time of death, no dissolved oxygen could be detected in any of the non-aerated dilutions. (See Fig. 3.)

All the aerated dilutions were aerated for 48 hours before introducing the fish. In the 1 to 50 dilution, however, even this preliminary aeration was not sufficient to maintain an oxygen reserve, for the fish showed all signs of oxygen hunger and died in a comparatively short time. No dissolved oxygen could be detected in the dilution at the time of death of the fish.

In the aerated 1 to 100 and 1 to 200 dilutions, a dissolved oxygen content was maintained. The fish showed no signs of oxygen hunger, and many lived for 28 days, when the experiment was concluded. However, they were not as active as the fish in the control tanks. They made much less effort to evade capture. Their respiratory rate was slightly increased. They were much more susceptible to injury and small wounds

became very raw. The sulphite liquor did not appear to be particularly irritating, for they were never seen to rub themselves against the sides of the tank.

Besides slightly increasing their respiratory rate, the sulphite liquor also seemed to interfere with the utilization of oxygen. In the non-aerated control, black bass were able to withstand a period when the dissolved oxygen content was less that 1.0 part per million. They lived

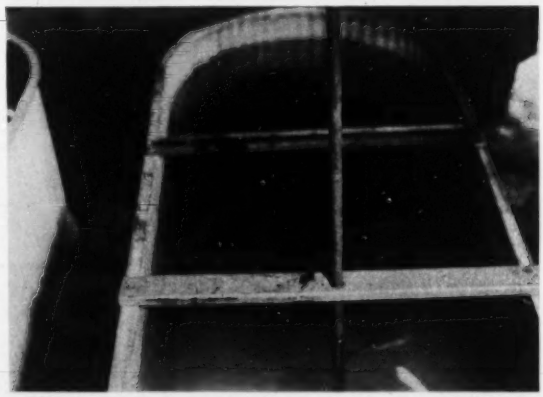

FIG. 3.—A non-aerated dilution with dead or dying fish at the bottom of the tank.

only two hours when placed in a 1 to 50 dilution that had been aerated so that its dissolved oxygen was over 2.0 p.p.m. Whether the sulphite liquor decreased the absorptive power of the gill membranes, disturbed the equilibrium of gaseous exchange in the blood or increased the general metabolic rate, was not determined. The last assumption does not appear probable, as there was no evidence of increased activity or hyper-excitability of the fish while in contact with the liquor. In all dilutions, a considerable amount of slime developed on the sides of the tanks. The question of mechanical obstruction of the gills might be raised, but microscopic examination of the gill filaments showed them to be free from any slime coating.

The fish that died in these aerated dilutions showed no unusual symptoms. This is in accordance with Belding's ('27) [6] observations. Autopsies of the dead fish and those killed at the end of the experiment were carefully made. All organs except the gall bladder appeared to be normal. In practically every case, the gall bladder was gorged with a

watery bile, which was straw colored, instead of the usual bluish green color. In some instances, the bladder was nearly as large as the liver. This abnormality was not found in any of the control fish and consequently could not be correlated with the oxygen supply. Neither was it related to the amount of food consumed.

Microscopic examination of the walls of the gall bladder and the liver did not show any striking pathology. However, in various areas in the liver, cells were vacuolated (indicating degeneration) and resembled certain pathological conditions of the mammalian liver resulting from toxins. These findings may be interpreted as due to the toxic effect of waste sulphite liquor, or one or more of its by-products formed during oxidation, which interfered with the normal excretion of bile by the liver and also suppressed the normal activity of the smooth muscle of the bladder and its ducts, thus preventing the escape of the watery fluid into the intestine. This paper does not attempt to explain how the sulphite liquor causes these abnormalities, but merely aims to correlate the gross and microscopical findings with exposure to the liquor.

The perch were much less resistant, both to the liquor and to low oxygen tension, than were either the blue-gills or the large mouth black bass. Shelford ('18) [8] rates the perch as more resistant than the black bass. In these experiments, just the reverse was found to be true.

The sulphite liquor is decidedly acid in its reaction. However, in the weaker concentrations, particularly when aerated, the pH remained on the alkaline side of neutrality, due to the alkalinity of the diluting water. In the non-aerated dilutions and in the 1 to 50 aerated dilutions, the reaction was definitely acid, the pH falling as low as 5.9. Fish, in general, have a low acid tolerance, but have been found living in waters having a pH as low as 4.6. Fish died more rapidly in the dilutions which were acid. Their deaths were presumably from lack of oxygen but the acidity may have been a contributing factor.

In these experiments, the biochemical oxygen demand results shed little light on the problem. As would be expected, the stronger the concentration, the greater the B.O.D. This demand decreased with oxidation but varied considerably, inasmuch as the growth of bacteria and fungi in the tanks and the accumulation of organic wastes added their increment to the total oxygen demand.

A second series was run, using sulphite liquor from a cook of hemlock chips. The results were practically the same. A third series was made, using the tail liquor from a process in which by-products were recovered from the original waste sulphite liquor. The results varied only in degree. This tail liquor was alkaline and had a much lower oxygen demand than the raw liquor, consequently the fish successfully withstood slightly higher concentrations of this waste recovery system effluent.

*Summary.*—These experiments indicate that while the main effect of pollution by waste sulphite liquor lies in the depletion of the dissolved oxygen content of the water, the waste also has a poisonous or toxic effect on fish life. It causes them to become sluggish, increases their respiration, interferes in some way with the utilization of oxygen and causes an interference with the normal excretion of bile by the liver and its discharge from the gall bladder. These toxic effects, however, appear in concentrations so great as to be almost outside the range of possibility of occurrence in any river in Wisconsin receiving sulphite pulp mill wastes, except within the immediate vicinity of sewer outlets. Furthermore, even after an exposure for 28 days in aerated dilutions of 1:200 many of the fish did not appear to be seriously affected.

What further effects the liquor might have can only be presumed. A slow acting poison might possibly be fatal after a longer period of exposure. Decreased activity might make them an easier prey for their enemies. Reproductive capacities might be interfered with, which would result in a great depletion of the fish in a polluted stream. But such are speculations and no evidence is presented to substantiate any of them.

## II. The Toxic Effects of Waste Sulphate Liquor (Black Liquor) on Fish

Black liqour, the effluent from the alkali cook of wood chips in the manufacture of sulphate (kraft) pulp, is generally considered to be harmful to fish, and in sufficient concentrations to be fatal to them. The oxygen demand of the liquor, while not as high as that of sulphite liquor (due to the salvage of about 85 per cent of the chemicals in the recovery process), is satisfied at the expense of the dissolved oxygen of the diluting water. Consequently, when this waste is discharged into a stream, it may cause the death of fish by depleting the dissolved oxygen content of the water. In addition, it has been suggested that the chemical constituents of the liquor, or substances produced by their decomposition, may also have a toxic effect on fish life.

The literature dealing with this particular problem is very meager. Nightingale and Loosanoff ('30),[10] reported that, with the dissolved oxygen content maintained above the critical point, a 1 to 15,000 dilution of black liquor was harmless to Chinook salmon fry and fingerlings, but that stronger concentrations produced deleterious effects. The extent and nature of the toxic effects of waste sulphate liquor on fish was investigated in a series of experiments which are reported herewith.

*Methods.*—The methods employed in this investigation were essentially the same as those described in Section I. The fish were exposed to the waste sulphate liquor in large tanks (250 gallon capacity). The

dissolved oxygen content was maintained by aeration. Controls of non-aerated dilutions and also of unpolluted lake water, both aerated and non-aerated, were employed. Physical conditions in the set-up were as uniform as possible.

The fish used were perch, blue-gills, large mouth black bass and rock bass. Only mature, hardy individuals of approximately the same size were used. Throughout the course of the experiment, they were frequently examined; their behavior was carefully watched and checked with that of the controls. All fish were autopsied at death; those which survived the experiment were killed and examined for gross abnormalities.

The experimental dilutions of the liquor used were 1 to 50, 1 to 100, 1 to 200 and 1 to 500. These concentrations are higher than any found in a river below Wisconsin sulphate mills, except near sewer outlets; but, as there was a definite time limit for the experiment, it was thought advisable to use higher concentrations so that any toxic effect might become evident in a shorter period of time. Routine determinations for dissolved oxygen (Theriault) [2] and biochemical oxygen demand and pH and temperature readings were made.

The sulphate liquor from which the dilutions were prepared was taken from the effluent pipe leading from a pulp mill digester to the strong liquor storage tank, before appreciable dilution by pulp wash water. The following analyses were made:

TABLE II.—*Analyses of Black Liquor Before and After Dilution and Aeration*

| | Before Dilution | 1 to 100 Dilution Aerated 30 Days |
|---|---|---|
| Total Solids | 261,680 p.p.m. | 2,076 p.p.m. |
| Fixed Solids | 113,080 " | 1,120 " |
| Volatile Solids | 148,600 " | 956 " |
| Soluble Solids | 258,438 " | 2,030 " |
| Suspended Solids | 3,242 " | 46 " |
| Fixed Suspended Solids | 1,060 " | 0 " |
| Oxygen Consumed | 320,000 " | 15,000 " |
| Total $SO_2$ | 2.2% | .0056% |
| Free $SO_2$ | 0.0% | .0049% |
| Combined $SO_2$ | 2.2% | .0007% |
| Specific Gravity | 1.13 | |

*Results and Discussion.*—The fish in the aerated control behaved in a normal manner. Aside from the perch, which were killed by an infection of Saprolegnia after 11 days, all but one lived over 50 days. When killed and examined no unusual findings were observed.

In the non-aerated, unpolluted-water control tank, the fish quickly used up the available oxygen, and thereafter the amount of oxygen ab-

sorbed at the surface was not sufficient for their needs; consequently, they exhibited all signs of oxygen hunger and most of them died from asphyxiation after a few hours. One perch, the blue-gills and the black bass survived a period when the dissolved oxygen was less than 0.9 p.p.m. The perch and blue-gills died after a few days, but the black bass lived 50 days. The dissolved oxygen never exceeded 2.4 p.p.m.

The fish exposed to the non-aerated dilutions of sulphate liquor died in a very short time. In the 1 to 50, 1 to 100 and 1 to 200 dilutions, all fish were dead within 30 minutes. In the 1 to 500 dilution, some fish (black bass) lived 45 minutes. The higher dilutions were extremely irritating to the fish. After introduction, they immediately swam to the surface, thrashed about, jumped, swam into the sides of the tank, gulped air. Examination at death showed a bleaching of the color markings. The mucous coating of the scales was coagulated. The gills were pale and corroded. Almost invariably they had disgorged their stomach contents. No dissolved oxygen could be detected in the dilution. In the 1 to 200 dilution, the signs of irritation were not so marked, otherwise their behavior was the same. Again no dissolved oxygen could be detected. In the non-aerated 1 to 500 dilution, the fish exhibited less evidence of irritation but showed all the usual signs of air hunger. At the time of death, the dissolved oxygen content of the dilution was still 2.0 p.p.m. After all respiratory movements had ceased, the heart was found to be beating. They apparently died of respiratory failure in the presence of oxygen normally sufficient to maintain life.

All the aerated dilutions were aerated for 48 hours before the fish were introduced in order to insure an adequate dissolved oxygen content. In the 1 to 50 dilution the fish behaved in the same manner as they did in the 1 to 50 non-aerated dilution. They jumped and thrashed about, swam at the surface and gulped air. All were dead within an hour. Examination at death showed color markings bleached, a heavy coating of coagulated slime over the body, gills pale and corroded. The dilution still showed 1.3 p.p.m. of oxygen.

In the aerated 1 to 100 dilution the majority of fish died within a few (9 to 14) hours, although some of the black bass lived for 42 hours. At the end of 12 hours, the dissolved oxygen was still above 3.0 p.p.m. The fish behaved in the same manner, although the dilution did not appear to be quite so irritating. Examination after death showed bleaching, coagulated mucous, pale "moth-eaten" gills. In many cases the conjunctiva was opaque and infiltrated with a brown precipitate. On autopsy, the gall bladder was found distended with a pale, watery bile that was acid in reaction, having a pH in some instances as low as 4.8. The pH of the bile of normal fish varied from 6.5 to 7.0. In the fish that have urinary bladders (black bass) the bladders were gorged with

a very acid urine. These conditions were never seen in the control fish.

The fish exposed to the 1 to 200 aerated dilution lived a longer period of time. Most of the fish lived 13 to 24 days, although one blue-gill and one rock bass lived 30 days (the end of the experiment). The dissolved oxygen was never below 3.7 p.p.m. This dilution was not nearly so irritating. The fish jumped and rubbed themselves against the tank at first, but soon showed no evidence of irritation. Bleaching and coagulation of mucous was not so marked. Before death the fish exhibited a series of phenomena which usually came on gradually and which was followed by death in a relatively short period of time. These behavioristic changes ordinarily occurred in the following order: surface swimming; slow, labored respiratory movements; weakness and inactivity, accompanied by a decrease or loss of response to stimuli; twitching of fin muscles; partial loss of equilibrium; sudden spasmodic or convulsive swimming movements; partial spastic paralysis of fin muscles, first of the pectoral fins, then the pelvic, the fins usually being held in abnormal positions; respiration slower and more labored; finally death from paralysis of respiratory muscles. On autopsy, immediately after cessation of respiratory movements, the heart was found to be beating, the gall bladder gorged with a pale, watery, acid bile and the urinary bladder (if present) dilated with a very acid urine. Microscopic examination showed definite pathology in the liver. Cells in the various areas were vacuolated and showed evidences of fatty degeneration.

The dissolved oxygen of the 1 to 500 dilution was at all times above the critical point. The fish in this dilution exhibited, in general, the same series of findings although certain stages might be less marked, others more evident. Some fish, particularly the perch, finally died of respiratory paralysis and autopsy showed the same general findings. The majority of the blue-gills, black bass and rock bass lived 30 days (the end of the experiment). Some of these evidenced at times certain of the general toxic signs, but eventually recovered. When killed and autopsied, practically all showed large gall bladders and acid bile. The liver pathology in these cases was less obvious.

These findings indicate rather conclusively that waste sulphate liquor in sufficient concentration is toxic to fish. In the higher concentrations the liquor is decidedly irritating and coagulates the protective mucous coating of the body. This is probably due to the high alkalinity of the liquor. The pH of the higher concentrations was above 10.5. The weaker dilutions, that had a pH of less than 9.6 were not nearly so irritating. The alkalinity decreased with oxidation (aeration) of the waste. Fish introduced into the higher concentrations that had been aerated for some time and whose pH was around 8.5, showed no signs of irritation. The fish responded to the irritating factor by secreting copious

amounts of slime which was almost immediately coagulated. This irritating factor probably also caused the opaqueness of the conjunctiva. Fishermen have often reported blindness in fish living in sulphate polluted waters.

In the non-aerated dilutions, where the dissolved oxygen dropped to zero, the fish died from asphyxiation, although the irritating factor was undoubtedly a contributing cause, for the gill filaments were always found to be ragged and corroded. In the 1 to 500 non-aerated and the 1 to 50 aerated dilutions, the fish died when the dissolved oxygen content was higher than that of the non-aerated control which many of them were able to withstand. The sulphate waste appears to act in a manner which interferes with the proper utilization of oxygen.

The series of toxic signs which developed in the fish that were exposed to sulphate liquor dilutions in which the dissolved oxygen content was maintained well above the critical point, indicate conclusively that the fish died of respiratory failure. Certain sulphur compounds are known to be toxic to mammals, where they act as depressors of various medullary centers. Poisoning by these compounds results in convulsions and spastic paralysis. The victims die of respiratory failure due to paralysis of respiratory muscles. The excretions and secretions of such animals are more acid than normal. The toxicity of waste sulphate liquor to fish can probably be explained on this basis. Certain sulphur-containing constituents act through the central nervous system, causing spastic paralysis of muscles which would result in death from respiratory failure. The equilibratory derangements would follow the partial loss of activity of the fin muscles. Paralysis of the sphincters at the mouths of the gall and urinary bladders would prevent the normal discharge of the contained fluids. High acidity of excretions are characteristic of this type of poisoning. The pathology found in the liver can be correlated with the increased acidity of the bile.

What constituents of the liquor are responsible for the toxicity is not known. However, methyl mercaptan, known to be contained in waste sulphate liquor, and the compound which imparts the "rotten cabbage" odor to the liquor, is known to be toxic. Fish were exposed to water containing less than 1 part per million of methyl mercaptan (the dissolved oxygen content being at all times above 6.8 p.p.m.). They lived not over 11 hours and exhibited most of the toxic signs previously described for sulphate liquor. This indicates that methyl mercaptan may be one of the toxic factors in waste sulphate liquor.

Prolonged aeration decreased the toxicity of the liquor. Fish exposed to dilutions that had been aerated for a long time live for much longer periods of time than when introduced at the beginning of aera-

tion. Aeration decreased the oxygen demand of the liquor and apparently oxidized, drove off, or otherwise reduced the toxic constituents.

The concentrations used in these experiments were definitely higher than any which would usually be found in a river, except in proximity to mill outlets. Whether extremely low concentrations, working over a long period of time, would produce chronic sulphate poisoning, is not known. However, fishermen have many times reported that fish taken from sulphate polluted waters, are oftimes blind, sluggish and otherwise abnormal in their behavior. These observations would not be contrary to an interpretation of a mild, chronic sulphate poisoning.

*Conclusions.*—Waste sulphate liquor is definitely irritating to fish in concentrations of 1 to 500 or higher. It coagulates the mucous covering of the scales, bleaches the color markings, corrodes the gills and makes the conjunctiva opaque. It robs the diluting water of its oxygen and the fish are asphyxiated. Aside from these effects the sulphate (black liquor) waste is definitely toxic (especially in dilutions of 1 to 200 or less), and kills fish in varying periods of time depending upon the concentration of waste. The signs of poisoning include a decreased respiratory rate, decreased activity, loss of general sensibility, twitching of muscles, equilibratory derangements, spasmodic movements, spastic paralysis of fin and opercular muscles, and finally, death from respiratory paralysis. Autopsy findings include engorgement of gall bladder and urinary bladder (when present) and an increase in the acidity of the bladder contents. The liver shows definite pathology. The toxicity of the liquor is decreased by aeration.

## III. The Effect of Ozone Treatment on the Toxicity of Waste Sulphate Liquor (Black Liquor) to Fish

Through experimental work described in Section II, it has been demonstrated that waste sulphate liquor (Kraft) in certain concentrations is definitely harmful to fish. Besides being irritating and depleting the diluting water of the dissolved oxygen necessary for maintenance of fish life, the so-called "black liquor" was found decidedly toxic. In a 1 to 200 dilution, in which the dissolved oxygen content was maintained by aeration above 3.7 p.p.m., the majority of fish died in from 13 to 24 days, exhibiting a series of behavioristic signs which finally resulted in death from paralysis of the respiratory muscles. Prolonged aeration decreased the biochemical oxygen demand as well as reduced the toxicity of the liquor to fish. Apparently, aeration results in the oxidation of certain constituents of the liquor which have a great affinity for oxygen and which are toxic to fish. Now, if prolonged treatment with molecular oxygen of the air could bring this about, the same results

should be produced in a much shorter period of time by employing a more powerful oxidizing agent. Ozone, by virtue of its instability and the powerful oxidizing capacity of nascent oxygen, should rapidly decrease the deleterious effects of the liquor. Ozone itself is toxic, but, due to its instability, especially in the presence of organic matter, it would not remain as such for any appreciable length of time. It was, therefore, thought advisable to determine by experimentation whether the deleterious effects of waste sulphate liquor could be practically and effectively reduced by ozonation.

*Methods.*—Samples of sulphate liquor were treated with ozone from a generator which produced .33 cu. ft., of ozonized air per minute.* Its efficiency was such that it delivered 6 gms. of ozone per hour at a concentration of 10.5 mgs. per L. Using the same amount of liquor in each case the following ozonations were made:

TABLE III.—*Amounts of Ozone Applied to Sulphate Pulp Mill (Black Liquor) Wastes*

| Length of Treatment | Total Gms. $O_3$ Used | Gms. $O_3$ per Gal. |
|---|---|---|
| 10 min. | 1 | .4 |
| 20 " | 2 | .8 |
| 30 " | 3 | 1.2 |
| 60 " | 6 | 2.4 |
| 120 " | 12 | 4.8 |
| 180 " | 18 | 7.2 |

The liquor was ozonated at a temperature of 50° C. to decrease foaming. Tests were made from time to time to determine that all the ozone generated was being used by the liquor.

These samples were then diluted 1 to 100 and aerated to maintain a constant dissolved oxygen content. Controls of aerated 1 to 100 dilutions of untreated liquor and aerated, unpolluted water were used. Into these treated dilutions and controls healthy, mature fish were introduced. The fish used were perch, large mouth black bass, white bass, silver bass, rock bass and blue-gills. The physical conditions of the set-up and the routine examinations and determinations were the same as in the original work with sulphate liquor. The toxicity was judged by the length of life of the exposed fish and their behavior during exposure.

*Results and Discussion.*—The following table shows the percentage difference in length of life of fish in the 1 to 100 dilutions of sulphate liquor with various amounts of treatment with ozonized air, as compared with the untreated controls:

* Grateful acknowledgment is made to the U. S. Ozone Company who placed the ozone generator at our disposal, and to Mr. A. B. Conant whose aid was invaluable in the process of ozonating the waste liquor.

TABLE IV.—*Longevity of Fish in 1 : 100 Dilutions of Ozonated Sulphate (Kraft) Waste Liquor as Compared with Untreated Liquor*

| Species of Fish | Length of Ozone Treatment (in Minutes) | | | | | |
|---|---|---|---|---|---|---|
| | 10 | 20 | 30 | 60 | 120 | 180 |
| Black Bass | 114% | 122% | 47% | −18% | 25% | 53% |
| White Bass | 13 | 21 | 29 | | | |
| Silver Bass | −14 | 5 | 20 | 13 | 55 | 43 |
| Perch | 30 | 15 | 60 | 10 | 41 | 34 |
| Rock Bass | | | | 4 | 13 | 114 |
| Blue-Gills | | | | −23 | 176 | 288 |
| Average of all Fish | 36% | 41% | 39% | − 3% | 62% | 106% |

As far as could be ascertained, the signs which were exhibited before death by the fish in the ozone-treated dilutions were indistinguishable from those which preceded death of the fish confined in the untreated sulphate liquor. There was no evidence of any toxic effect which might be ascribed to ozone. The dilutions of treated liquor were irritating and partially coagulated the mucous covering of the body. Ozonation did not appreciably change the pH of the dilutions. The same series of behavioristic signs, which were characteristic of sulphate poisoning, were exhibited. Death was from paralysis of the respiratory mechanism. Autopsy, immediately after cessation of respiratory movements, revealed a heart still beating, a gall bladder gorged with a pale, watery, acid bile. The same indications of pathological change in the liver were observed. In those fish which had a urinary bladder, this organ was distended with an abnormally acid urine. The only difference between the fish in the treated dilutions and those in the controls was that on the average the fish lived longer in the ozonated dilutions than they did in the untreated sulphate liquor. Aside from the dilution which was made from liquor treated with ozonized air for 60 minutes (for which we have no explanation) it appeared that ozonation of sulphate liquor decreased the toxicity of the liquor to fish and that the decrease was roughly proportional to the length of treatment. The difference in toxicity due to ozonation, while significant, was not outstanding. Even in the extreme case where the average length of life of all fish was 106 per cent longer than that in the untreated control, all but one fish was dead within 16 days.

It is apparent that ozonation did not fulfill the expectations. It was obvious that during the process of ozonation the total amount of oxygen delivered to the sample of sulphate liquor in the form of ozone, was not sufficient to satisfy completely the oxygen demand. However, it was supplied in a quantity sufficient to decrease this demand to a marked

degree, if it attacked the same part of the complex molecule which is ordinarily oxidized by molecular oxygen. Prolonged aeration of sulphate liquor decreases the biochemical oxygen demand, the oxygen consumed and the total solids. Ozonation, at least to the extent of 7.2 gms. of ozone per gallon, did not show significant changes in any of these determinations. The oxidation due to ozone appears to involve some component of the sulphate liquor which is not concerned with the B.O.D. or oxygen consumed determinations. The only substance which was found to vary with the amount of ozonation was sulphur as hydrogen sulphide. Figure 4 shows the percentage of reduction in $H_2S$ of sul-

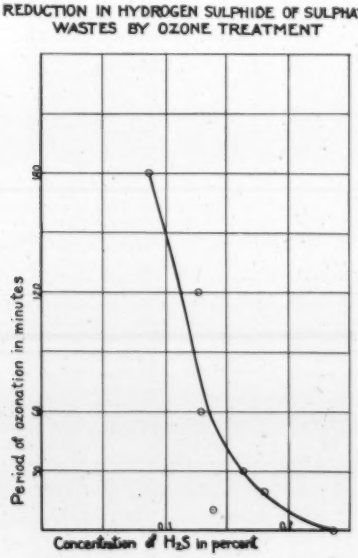
REDUCTION IN HYDROGEN SULPHIDE OF SULPHATE WASTES BY OZONE TREATMENT
Period of ozonation in minutes
Concentration of H2S in percent
0.1
0.2

FIG. 4.

phate liquor by varying amounts of ozone treatment. Hydrogen sulphide is in itself quite toxic, but its toxic effects are not sufficiently similar to those of whole sulphate waste to justify a conclusion that the liquor owes its toxicity to its $H_2S$ content. It may, however, be one of its toxic factors.

There is additional evidence that oxidation of the sulphate liquor by nacent oxygen during ozone treatment is not the same as oxidation by molecular oxygen and that chemical changes are set up which do not end with the cessation of the ozonating process. To determine the amount of dissolved oxygen present in the sulphate liquor, Theriault's modification of the Winkler method had to be employed.[9] This method calls for a preliminary treatment with alkaline hypochlorite. The amount of hypochlorite necessary is dependent upon the concentration of the sulphate liquor. As aeration progresses the amount of hypochlorite used gradually decreases. At the end of the second day of aeration of ozonated liquor, the amount of hypochlorite suddenly increased to double the amount previously used. This phenomenon was observed in all the ozonated dilutions. It was first thought that this might be correlated with a sudden growth in the bacterial content. However, the greatest growth at that stage was present in the untreated dilution where no fluctuation in the amount of necessary hypochlorite was found. It seems probable that this is an expression of some chemical change which was instigated by the previous ozone treatment.

The characteristic "rotten cabbage" odor of waste sulphate liquor, due to methyl mercaptan, was eliminated by ozonation.

*Summary and Conclusions.*—Fish of different species were exposed to dilutions of waste sulphate liquor which had previously been treated with varying amounts of ozone. Untreated liquor of the same dilution was used as a control. The toxicity of the treated liquor was measured by the length of life and the behavior of fish exposed to the dilutions. The degree of toxicity was compared with that of untreated liquor to determine whether ozone treatment was a satisfactory method for decreasing the toxicity of sulphate liquor to fish.

It was found that ozone treatment, even to the extent of 7.2 gms. of ozone per gallon, did not markedly decrease either the biochemical oxygen demand, the oxygen consumed value, or the pH of the raw liquor. The toxicity, however, was decreased somewhat; in general, the longer the period of ozone treatment the less toxic was the liquor. However, the decrease in toxicity was not sufficiently great to be considered important.

It was, therefore, concluded that the treatment of waste sulphate liquor with ozone, at least to the extent of 7.2 gms. of ozone per gallon, does not decrease the toxicity of the liquor sufficiently to justify the recommendation of its use as a detoxifying agent.

## IV. A Preliminary Report Concerning the Effect of Ozone Treatment on the Deleterious Effects of Waste Sulphite Liquor on Fish

It was pointed out in Section I that the harmful effects of waste sulphite liquor on fish were due primarily to the depletion of the dissolved oxygen content of the diluting water. But the liquor in high concentrations was also found to be toxic to fish. Prolonged aeration of toxic dilutions markedly reduced their toxicity.

Nightingale ('31) [11] reported that treatment of sulphite liquor with 0.8 to 1.0 gm. of ozone per gallon, decreased the oxygen demand and the acidity of the liquor, and consequently, the deleterious effects of the liquor on the fish. He recommended this procedure as a practical method of controlling sulphite liquor pollution of rivers. It had been demonstrated previously (see Section III) that ozonation, even to the extent of 7.2 gms. of ozone per gallon, had little effect in decreasing the toxicity of waste sulphate liquor. Preliminary experiments were, therefore, conducted to test the effect of ozone treatment on the toxicity of sulphite liquor to fish.

*Methods.*—Samples of waste sulphite liquor were ozonated by bubbling through them ozonized air from a generator which produced 6 gms. of ozone per hour. The liquor was ozonated in the raw state at a temperature of 20° C. Five samples were treated with the amounts of ozone, shown in Table V. These treated samples were then diluted 1

Table V.—*Amounts of Ozone Used in Treatment of Samples of Waste Sulphite Liquor*

| Length of Treatment | Amount of $O_3$ per Gallon |
|---|---|
| 15 min. | .6 gms. |
| 30 min. | 1.2 gms. |
| 45 min. | 1.8 gms. |
| 60 min. | 2.4 gms. |
| 90 min. | 3.6 gms. |

to 50 with lake water. The dilutions were aerated to maintain a residual dissolved oxygen content above the critical point. In the original experiments with sulphite liquor a residual dissolved oxygen content could not be maintained in the 1 to 50 dilution at the rate of aeration used at that time. By increasing the rate of aeration, it was found that an adequate oxygen supply could be maintained in such a dilution. Aerated controls of untreated 1 to 50 dilutions of the liquor were used. Into each dilution an equal number of fish were introduced. Perch, large mouth black bass and blue-gills were used. These fish had been previously acclimated to confinement in tanks in the laboratory. They were selected for their hardiness and uniformity of size. The usual

routine examination of the fish and determinations and tests on the dilutions were made. The degree of toxicity was determined by comparing the behavior and length of life of the fish exposed to the ozonated dilutions, with that of the fish confined in the untreated controls.

*Results and Discussion.*—The following table indicates the per cent mortality and the average length of life of fish that died in the ozone treated and untreated dilutions of waste sulphite liquor.

TABLE VI.—*Mortality and Length of Life of Fish Exposed to Ozonated Sulphite Waste Liquor*

| 1 to 50 Dilution | Mortality, Per Cent | Average Length of Life, Days |
|---|---|---|
| Untreated control—no $O_3$ | 30 | 7.6 |
| 15 min. — 0.6 gms. $O_3$ | 20 | 11.7 |
| 30 " — 1.2 " " | 10 | 8.0 |
| 45 " — 1.8 " " | 25 | 7.8 |
| 60 " — 2.4 " " | 20 | 7.2 |
| 90 " — 3.6 " " | 40 | 9.6 |

It is apparent that the mortality rate cannot be correlated closely with the degree of ozonation. The highest and lowest rates both occured in ozonated dilutions. The highest rate was in the sample which received the longest ozone treatment. With the exceptions of the dilutions which received the least and the greatest amount of ozone treatment, the average length of life of fish in the liquor was not changed by ozonation; and even in the exceptions, the per cent of increase over the control was not great. This does not agree with Nightingale's report, which indicated a marked decrease in the mortality of fish exposed to ozonated sulphite liquor.

The fish that died in the ozonated dilutions exhibited the same behavior and toxic signs as those that died in the untreated controls. These signs of toxicity were identical with those described in the original report, namely, sluggishness, increased respiratory rate, a decrease in the ability to utilize oxygen, as evidenced by signs of oxygen hunger in the presence of a dissolved oxygen content well above the normal critical point. Autopsy of the fish that died in all dilutions showed in almost every case a gall bladder gorged with a pale, watery bile, whose reaction was more acid than normal. Histologically, the liver showed areas of vacuolated cells. From the qualitative standpoint, ozonation did not appear to change the toxicity of sulphite liquor to fish.

Analysis of the treated and untreated liquors showed that ozonation did not decrease to any significant extent the values for oxygen consumed, acidity, biochemical oxygen demand or total solids. Nightingale reported that ozonation to the extent of 1.0 gm. of ozone per gallon markedly decreased these values. He also reported a reduction of the

iodine absorption values, indicative of $SO_2$, or its equivalent. Samples used in these studies showed no such reduction.

Aeration, after dilution, decreased the oxygen demand as well as the acidity of both the ozonated and the untreated liquors. The amount of these reductions was practically the same in each case, regardless of the amount of ozonation.

It would appear from these findings that the nascent oxygen from ozone did not oxidize those waste liquor constituents that were oxidized by the molecular oxygen delivered during prolonged aeration. No evidence is offered in support of this, other than the observations that prolonged aeration decreased the oxygen demand and the acidity, which results the ozone failed to accomplish.

Another series of observations, for which no adequate explanation is offered, is thought to be important enough to report. With a constant and uniform aeration rate in all dilutions, and with the same number of fish in each tank, the dissolved oxygen content of any dilution was inversely proportional to the amount of ozonation it had received; the longer the liquor was ozonated, the lower the dissolved oxygen content of the dilution at any given time. This held true for the first 4 to 5 days of aeration. Later, during the 6th to 8th days, the ratio of dissolved oxygen content to degree of ozonation was reversed; the longer the sample had been ozonated, the greater the amount of dissolved oxygen the dilution contained. After the 10th to 12th day the amount of dissolved oxygen was practically the same in all dilutions. From these observations it would appear that ozonation of sulphite waste liquor increases the rate of subsequent oxidation by molecular oxygen, and, consequently, more rapidly decreases the total amount of substances capable of being oxidized by molecular oxygen. This interpretation of our findings was not confirmed by the biochemical oxygen demand determinations, which should have shown a more rapid reduction in the dilutions that had received the greater amounts of ozonation.

*Conclusions.*—From these preliminary experiments no final conclusions can be drawn. The results indicate however, that ozone treatment of waste sulphite liquor, to the extent of 3.6 gms. of ozone per gallon of raw liquor, does not reduce the oxygen demand or the acidity of the liquor to any significant extent, nor does it effectively decrease the toxicity of the liquor to fish.

## V. Do Wood Fibers Clog the Gills of Fish?

It has so often been stated that wood fibers clog the gills of fish and cause their death by suffocation that many have come to consider it a true statement. Fishermen on paper mill rivers have observed fish with

their whole gill chamber clogged with wood fibers. Little information of value is found in the literature concerning this problem. Knight ('01) [2] showed that trout lived for two weeks in a gruel of sawdust. During this time their gills were uninjured and when they were brought to autopsy only two small fragments of wood were found among the gill filaments.

Wood fibers, due to their small size might conceivably become a menace to gill-breathing forms. Waste waters from pulp and paper mills always contain wood fibers, the amount depending upon the efficiency of the recirculation or save-all processes used.

To test the effect of wood fibers on the gills of fish, a 2 per cent suspension (by wet weight) of pulp was made. This gruel-like mixture was agitated by a mechanical stirrer and the whole aerated to maintain dissolved oxygen. Fish were placed in this mixture. Many of them lived as long as three weeks. A non-aerated suspension was also made but fish confined in this tank died in a short time from lack of oxygen.

The fish were examined from time to time for fibers on their gills. As long as the fish remained healthy and active their gills were kept clean. Active fish, when taken from the tank and killed, and their gill filaments subsequently examined with a lens, always showed clean gills, practically devoid of fibers. Occasionally a few fibers would be found but never in sufficient numbers to be injurious. Pieces of these gills were sectioned and examined histologically. Only an occasional small fiber was found enmeshed among the gill filaments. The fish that died in these suspensions always were found to have their gills covered with fibers. However, as long as the respiratory movements were strong, fibers did not accumulate. It was only when the fish were dying that the fibers clogged their gills. This clogging undoubtedly hastened death but was not its primary cause. Excessive amounts of fiber in the water may decrease the resistance of fish, for it takes a greater expenditure of energy to force a fluid of gruel-like consistency through the gills than it does to breathe clean water.

It is easy to see the basis for the conception that paper fibers kill fish by clogging their gills. The finding of a group of dead fish with mouths and gills clogged with fibers seems *a priori* evidence that the fish were suffocated by the fibers. If, however, these fibers did not accumulate until the fish were in a dying condition, and their last efforts were not strong enough to force the fibers through the gill slits, then the interpretation is quite different.

These experiments lead to the belief that healthy fish are practically unaffected by wood fibers suspended in water. Results indicate that the fibers accumulate only when the fish are dying and the last respiratory efforts are not sufficiently strong to clean them from the gills.

Indirectly, however, wood fibers do have a deleterious effect on fish life. The accumulation of a mat of fibers on the stream bed prevents the normal growth of aquatic vegetation and animal life which serve as fish food; it destroys spawning beds and so interferes with the normal reproduction cycle; and, finally, its decomposition depletes the dissolved oxygen content of the water.

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# Editorial

## CLEAN STREAMS

The study of stream pollution is of primary importance as the fundamental basis for decisions concerning the type and degree of sewage treatment. The scientific study of stream conditions is a complex problem, but an exceedingly interesting one. Such investigations include physical, chemical and biological sciences. A river is not an inanimate thing, but it simulates some of the functions of life. The self-purification of a polluted river may be likened to the recovery of a living organism from disease. Because of this biological nature of rivers, studies of stream pollution in the past have dealt mainly with ecological data, primarily of a qualitative nature. Classic studies of rivers in England and Germany were concerned with the numbers and types of micro-organisms and chemical analyses of empirical nature; no attempt was made to express in mathematical terms the degree of pollution as balanced against the capacity for self-purification.

It is to the credit of American sanitary engineers and chemists that the modern basis of study of stream pollution and self-purification rests upon an engineering and mathematical foundation much more informative than the older records and reports. Professor Earle B. Phelps and Messrs. H. W. Streeter and E. J. Theriault deserve much of the credit for the development of the improved system of stream study. The conception of oxygen balance was introduced by Professor Phelps many years ago. His conceptions have been expanded and refined by Mr. Streeter, who has had at his command analytical methods improved by Mr. Theriault. A fairly complete description of the entire procedure is given by Mr. Streeter in this issue, to be followed by a second contribution in the next issue. A careful study of these papers should be of great interest to all sanitary engineers and chemists engaged in the treatment and disposal of sewage.

Many valuable studies of stream pollution have been made in the United States. One of the most interesting studies of several decades ago was that of the Potomac River, made under the direction of Dr. Allan J. McLaughlin. Professor Phelps contributed valuable material to this report and brought out the importance of photo-synthesis in the lower section of the river. This effect had also been noted during classic studies of the Illinois River prior to, and just following the opening of the Drainage Canal in 1900. Without a doubt, the Ohio and Illinois

Rivers have been studied more thoroughly than any other rivers in this country. The work of the U. S. P. H. S. on the Ohio River has continued since 1914; these studies are the foundation of the modern system of oxygen balance. Of equal importance are the studies of the Illinois River, particularly since 1920. The large amount of pollution contributed to this river at the source, the length of the river, and its importance for commerce, fishing and recreation combine to focus particular attention on the results. The Sanitary District of Chicago has accumulated a large amount of information bearing on this problem, some of which is referred to by Mr. Streeter. The Engineering Board of Review of the Sanitary District, under the direction of Mr. H. P. Eddy, contributed a noteworthy report to the annals of stream purification.

Other rivers have also been studied in detail, particularly the Mississippi River near Minneapolis. The Connecticut, Delaware and Hudson Rivers have been investigated with reference to water diversion and litigation between states. The Sangamon River in Illinois, Trinity in Texas, and Naugatuck in Connecticut also come to mind. For many years frequent reference is found to the sane policy of stream regulation practiced by the Pennsylvania Water Board. Wisconsin is noted for studies of the effect of industrial wastes on streams. The paper by Warrick and Cole in this issue is an interesting contribution to this record. Studies in Massachusetts have extended over many years. The control of stream pollution in Michigan is becoming of increasing importance.

These frequent and extensive investigations impress one with the fact that the importance of clean streams is realized by sanitarians. It is imperative that all possible improvements in technic be adapted to use in stream studies. The abatement of pollution and the return to clean and decent streams is one of the most important duties of a sanitary engineer.

The aesthetic values inherent in beautiful streams must not be forgotten. To all nature lovers a stream is a constant pleasure and inspiration. Mark Twain, in "Life on the Mississippi," records his impression of that noble stream as follows: "And then you have the shining river, winding here and there and yonder, its sweep interrupted at intervals by clusters of wooded islands threaded by silver channels; and you have glimpses of distant villages, asleep upon capes; and of stealthy rafts slipping along in the shade of the forest walls; and of white streamers vanishing around remote points. And it is all as tranquil and reposeful as dreamland, and has nothing this-worldly about it—nothing to hang a fret or worry upon."

F. W. M.

# Proceedings of Local Associations

## NEW YORK STATE SEWAGE WORKS ASSOCIATION

### Seventh Annual Meeting, New York City, January 15, 1935

The Seventh Annual Meeting of the New York State Sewage Works Association was held January 15, 1935, at the Hotel McAlpin, New York City. The attendance of 211 was the largest ever recorded in the history of the Association. At the business meeting, Messrs. Charles C. Agar (Albany), Thorndike Saville (New York) and William W. Watkins (Oneonta) were elected to the Executive Committee in place of Messrs. J. L. Barron, A. F. Dappert, and L. L. Luther whose terms of office expired. Mr. Morris M. Cohn of Schenectady was elected president and Mr. Robert C. Wheeler of Albany, vice-president. A. S. Bedell, State Department of Health, Albany, was reappointed secretary-treasurer.

At the general business meeting, it was voted to cooperate with the State Department of Health and the Mayors' Conference in holding a school for sewage works operators in Albany during the month of April this year. The report of the special committee on "Rating of Sewage Treatment Plants" was adopted. Mr. C. A. Emerson, Chairman of the Federation of Sewage Works Associations, indicated that the Federation felt this was a valuable project and proposed to offer a substantial grant of money for carrying on the work of the committee.

At the morning session, H. H. Hendon, Sanitary Engineer of the Jefferson County Sewer Commission, presented an unusually interesting paper on "The Shades Valley Chemical Precipitation Plant in Birmingham, Alabama," the discussion on which was opened by Professor Charles G. Hyde and Linn H. Enslow. At the luncheon President Edmund B. Besselievre presented the Kenneth Allan Memorial award for 1934 to Alden E. Stilson for the most meritorious paper of a technical and research nature presented during the year. Professor Charles Gilman Hyde of Berkeley, California, was the principal speaker and gave a very stimulating talk on "Some Comments on Sewage Treatment Problems and Trends."

At the afternoon session, Wellington Donaldson gave a timely paper on "Sewage Plant Laboratories," the discussion of which was led by T. M. Riddick of New York University. J. S. Pecker of Philadelphia, Pennsylvania, presented a paper on "Centrifugal Dewatering of Sludge" with particular reference to the work at Collingswood, N. J. The discussion on this paper was opened by Colonel Frank J. Taintor and a

written discussion by C. E. Keefer of Baltimore, Maryland. Dr. M. L. Isaacs of Columbia University gave a very valuable talk and demonstration on "A New Colorimetric Method for Dissolved Oxygen" which was discussed by F. W. Gilcreas, Associate Sanitary Chemist of the New York State Department of Health.

John R. Downes of Bound Brook, N. J., gave a brief description illustrated by motion pictures on "The Features of Joint Plainfield, North Plainfield and Dunellen Works," noting particularly the work on conditioning and spray drying of digested sludge.

In the evening the Association joined with the Sanitary Engineering Section of the A. S. C. E. in their annual banquet, at which Deputy Commissioner Walter D. Binger of the New York City Department of Sanitation was principal speaker. Mr. Binger discussed in a most interesting manner the work of the Department of Sanitation of New York City.

A post convention trip was made to the Joint Plainfield, North Plainfield, and Dunellen Sewage Treatment works at Bound Brook, N. J., where a full scale installation has been made for conditioning and spray drying digested sludge. Bus transportation and buffet luncheon was furnished the seventy persons who took the trip through the courtesy of the Industrial Associates, Inc., and John R. Downes, Supervising Engineer of the treatment plant.

During the afternoon session on Tuesday, the Association unanimously adopted the following resolutions:

(1) WHEREAS, The N. Y. S. S. W. A. has lost through death this past year one of its outstanding and loyal members and the Sanitary Engineering profession an authority of international reputation, George W. Fuller,

*Be it resolved that*, this Association record its great appreciation of his inestimable contribution to the art of sewage disposal and express its regret at his untimely passing, and,

*Be it further resolved that*, a copy of this resolution be transmitted to his family and to his surviving business associates.

(2) WHEREAS, the N. Y. S. S. W. A. has lost, also by death, another of its loyal and active members, Alfred W. Evans of Tonawanda, New York,

*Be it resolved that*, this Association record its regret at his death, and,

*Be it further resolved that*, their resolution be transmitted to his family.

(3) WHEREAS, the New York State Planning Board in its report to his Excellency, Governor Lehman, has recommended strengthening legislation for the control of water pollution,

*Be it resolved that*, this Association place itself on record in general approval of such a policy, and

*Be it further resolved that*, copies of this resolution be transmitted to Governor Lehman and to the New York State Planning Board.

A. S. BEDELL,
*Secretary.*

*Note.* The Spring Meeting of the New York State Association will be held May 24–25, 1935, at Poughkeepsie.

## ANNUAL MEETING OF THE BOARD OF CONTROL OF THE FEDERATION OF SEWAGE WORKS ASSOCIATIONS

The annual meeting of the Board of Control of the Federation of Sewage Works Associations was held in the office of the Chemical Foundation in New York City on Friday morning, January 18, 1935, at 10 A.M.

The Chairman, Mr. C. A. Emerson, Jr., presided. Owing to absence of the Secretary-Treasurer on account of illness, Miss Theresa A. Kraus, Secretary to the Business Manager, served as secretary of the meeting. The roll was called and the following were found to be present in person:

| *Name* | *Representing* |
|---|---|
| H. G. Baity | North Carolina Sewage Works Association |
| E. B. Besselievre | New York Sewage Works Association |
| C. H. Eastwood (for Wm. J. Orchard) | Member at Large |
| C. A. Emerson, Jr. | Pennsylvania Sewage Works Association |
| Arthur P. Miller | Federal Sewage Research Association |
| F. W. Mohlman | Central States Sewage Works Association |
| Earle B. Phelps | Member at Large |
| Wm. M. Piatt | North Carolina Sewage Works Association |
| Willem Rudolfs | New Jersey Sewage Conference Group |

The following were represented by proxy:

| | |
|---|---|
| A. E. Berry | Canadian Institute on Sewage and Sanitation |
| F. G. Browne | Ohio Sewage Works Conference Group |
| J. W. Bugbee | Member at Large |
| F. K. Bullen | Oklahoma Water and Sewage Conference |
| Morris Cohn | New York Sewage Works Association |
| W. D. Collins | Federal Sewage Research Association |
| H. J. Darcey | Oklahoma Water and Sewage Conference |
| F. M. Ehlers | Sew. Div., Texas Sect., S. W. W. A. |
| R. E. Fuhrman | Missouri Water and Sewage Conference |
| E. S. Glenn | Missouri Water and Sewage Conference |
| R. F. Goudey | California Sewage Works Association |
| H. R. Hall | Md.-Del. Water and Sewage Association |
| C. G. Hyde | Cal. Sewage Works Association |
| W. S. Mahlie | Sew. Div., Texas Sect., S. W. W. A. |
| H. E. Moses | Pennsylvania Sewage Works Association |
| H. A. Olsen | Michigan Sewage Works Association |

J. R. Rumsey .....Michigan Sewage Works Association
H. W. Streeter .....Member at Large
A. M. Veitch .....Canadian Institute on Sewage and Sanitation
Abel Wolman .....Md.-Del. Water and Sewage Association

## Reports of Officers

The Chairman remarked briefly on the continually increasing strength of the Federation and the popularity and usefulness of Sewage Works Journal as indicated by the increase of membership in most of the affiliated organizations, the greater attendance at local meetings and increase in advertising. He also pointed out that the allotted districts of the 19 local associations include 28 of the States, comprising a population of approximately 93,000,000 or slightly over 75 per cent of the population of continental United States according to the 1930 census. In addition there are three active foreign affiliates, one being in Canada and the other two in England.

The report of the Secretary-Treasurer showed that the total net membership of the 19 affiliated organizations was 1468 after deduction of 36 dual memberships. This was an increase of 56 over the preceding year. At the end of the year the New York Association had the largest membership. The report noted that the Central States Sewage Works Association had added Minnesota as a member state.

The report of the Business Manager showed that at the end of the year a total of 1850 persons received the Journal. Of this number 1476 were members of local associations, 320 were non-member subscribers and the remaining 34 consisted of gratis and exchange subscriptions. It was noted with interest that of the member subscribers 133, or approximately 10 per cent, reside outside the United States and that of the non-member subscribers 155, or nearly one half, reside in foreign countries.

The report showed that during the year 1934 contract advertising averaged 15.5 pages per issue, the highest average for any of the six years of the Journal's history.

Earle B. Phelps, Chairman of the Research Committee, reported that the committee is engaged on preparation of a critical review of literature published during 1934 on research in sewage chemistry, sewage treatment and stream pollution and hoped to have it completed in time for inclusion in the March issue of Sewage Works Journal.

W. D. Hatfield, Chairman of the Standard Methods of Sewage Analysis Committee, reported that the tentative draft of standard methods of sewage analysis which was completed during the year had been mimeographed and sent out to some twenty interested parties for criticism.

W. M. Piatt, Chairman of the Finance Committee, made a verbal

report of the activities of his committee in soliciting advertising and stated he was of the opinion that 1935 would bring even better results than their 1934 efforts.

Upon motion, which was duly seconded nad carried, the reports of the various committees were approved.

## New Business

The applications of the Kansas Water and Sewage Works Association for affiliation was discussed. It was voted to approve the application, conditioned upon the making of certain minor changes in their Constitution which Mr. Streeter, Chairman of the Organization Committee, deemed essential that it might comply with requirements of the Federation Constitution governing affiliates. It was reported that Earnest Boyce, Secretary of the Kansas group had promised that these changes would be made at their next regular meeting.

The application of the Northwest Conference on Stream Pollution was given consideration and it was voted to approve the application provisionally, pending adoption of a suitable constitution at the first meeting of the Conference which it was understood would be held during May at Lewiston, Idaho.

Discussion was given to a proposition from Films of Commerce, Inc., for production of a two-reel motion picture film, on sewage disposal for inclusion in the National Health Council series. Some thirty copies of the film would be made and it would be available to public health officials, school teachers and other interested parties throughout the country. The cost of producing and distributing the films would have to be met by manufacturers of sewage plant equipment. It was voted that the Chairman appoint a committee of three to consult with the National Health Council and interested equipment manufacturers to determine whether the films would be proper and dignified propaganda and whether equipment manufacturers would be willing to guarantee the cost of production and the annual service and distribution charges.

Editor F. W. Mohlman asked the advice of the Board on several matters concerning the physical makeup and character of articles in Sewage Works Journal. Among the matters discussed was the value of abstracts in their present form and the problem of the increasing size of the Journal which in 1934 totalled 1208 printed pages. It was voted to ascertain the individual opinions of the subscribers as to the abstracts and also not to reduce the size of the Journal unless financial conditions should make it imperative.

Chairman Emerson informed the Board of the decision of the New York Sewage Works Association to attempt to rate the excellence of

operating records kept by sewage treatment plant operators throughout the State. After brief discussion the Chairman was instructed to notify the proper officers of the New York Association that the Board was anxious to assist in the work of the committee, as it was believed to be a valuable forward step, and to this end would agree to publish the report in full in an early issue of SEWAGE WORKS JOURNAL and to furnish the committee with 200 reprints free. The Chairman also advised the Board of a grant of $100 by The Chemical Foundation to the New York Association for the work of this committee and for some suitable award to operators of plants receiving the higher or highest ratings as might be deemed best by the Association.

The Board proceeded to the election of officers and selection of committees for the coming year, the following nominees being duly elected:

OFFICERS

*Chairman* ..... C. A. Emerson, Jr., Pa.
*Vice-Chairman* ..... James R. Rumsey, Mich.
*Business Mgr.* ..... W. W. Buffum, Member at large
*Secy. Treas.* ..... None to be elected this year
*Editor* ..... None to be elected this year

MEMBERS AT LARGE

W. W. Buffum, New York City
H. W. Streeter, Cincinnati
Wm. J. Orchard, Newark
Chas Gilman Hyde, California
Earle B. Phelps, New York City

EXECUTIVE COMMITTEE

C. A. Emerson, Jr., *Chairman*
James R. Rumsey
W. W. Buffum
Wm. J. Orchard
H. E. Moses, *ex officio*

CONSTITUTIONAL COMMITTEES

*Membership*
H. W. Streeter, Federal, *Chairman*
A. E. Berry, Canada
R. E. Fuhrman, Missouri

*Publication*
C. D. McGuire, Ohio, *Chairman*
Arthur P. Miller, Federal

W. E. Merrill, New England
Chas. Gilman Hyde, California
F. W. Mohlman, *ex officio*

*Coordination*

A. F. Dappert, New York, *Chairman*
C. G. Gillespie, California
R. C. Smith, New Jersey

*Research*

Earle B. Phelps, Member at Large, *Chairman*
Wm. Rudolfs, New Jersey
W. S. Mahlie, Texas
H. B. Baity, North Carolina
Abel Wolman, Maryland-Delaware

SPECIAL COMMITTEES

*Finance*

Wm. B. Piatt, North Carolina, *Chairman*
E. B. Besselievre, New York
Wm. J. Orchard, Member at large

*Standard Methods*

Wm. D. Hatfield, Central States, *Chairman*
Members to be selected by Chairman of Federation and Chairman of Committee.

Consideration was given to request of Charles Gilman Hyde for appointment of a committee to observe the development of chemical precipitation as a method of sewage treatment.

Mr. Hyde suggested a committee of nine members, of which three each would be selected by the Public Health Engineering Section of the American Public Health Association, the American Chemical Society and the Federation of Sewage Works Associations. The Secretary was instructed to request Mr. Hyde to advise the Chairman in more detail as to how such a committee could function and whether the suggestion had been adopted by either or both of the other associations. Likewise the Chairman was instructed to appoint three members if on further study he believed such a committee could do anything of value and if the other two associations should agree to such a committee.

There being no further business the Board of Control adjourned upon motion and vote.

H. E. MOSES,
*Secretary-Treasurer*

# Reviews and Abstracts

## REPORT OF THE WATER POLLUTION RESEARCH BOARD (GREAT BRITAIN) FOR THE YEAR ENDED JUNE 30, 1934

By H. T. Calvert

*Director of Water Pollution Research*

Although water supplies now received by consumers are in general much safer than some years ago, the need for greater vigilance is occasionally emphasized by outbreaks of water-borne disease. Fortunately, no outbreaks have occurred during the past year so serious as those of the previous year at Malton and Denby Dale. Exceptional conditions of weather have prevailed, however, causing anxiety to water authorities and inconvenience to consumers. The rainfall during 1933 was one of the lowest on record and the first half of 1934 was also very dry. In order to meet this situation, an Act of 1934 permits the Minister of Health to make orders during a limited period controlling the use and diversion of water by authorities and individuals. Through another act, financial assistance can be obtained from the government for water supply schemes in rural areas.

The drought has also had a detrimental effect on the quality of water in rivers into which sewage and trades wastes are discharged as less water than usual has been available for dilution. The importance of continued research in methods of sewage and trades waste treatment has been thus made apparent.

In this connection, attention is drawn to the need for systematic records of flow in the various rivers, in order that the dilution available at different times may be accurately assessed. In a recent committee report, the need of a systematic survey of water resources in Great Britain has been emphasized.

### Investigations in Progress

In the accompanying report of the Director of Water Pollution Research, brief descriptions are given of the results of various investigations in progress. Among those of particular interest to readers of this Journal are the following:

*Milk Factor Effluents.*—Further progress has been made in experiments on the conditions affecting the purification of effluents containing

milk by a process involving anaerobic fermentation followed by biological filtration of the fermented liquid. Anaerobic fermentation of mixtures containing one per cent of milk in water causes separation of most of the fat and some protein. The separated liquid can readily be oxidized on percolating filters with an oxidation efficiency of about 99 per cent. Experiments also have been made using the activated sludge process.

*Biological Oxidation of Fats and Soaps.*—Some experiments have been made on the the biological filtration of solutions of sodium stearate alone and in admixture with domestic sewage. The results have shown that soap in concentrations as high as 250 p.p.m. in sewage can readily be oxidized by this method, but that the process is not satisfactory for solutions of soap alone in water. The presence of soap in the sewage increases the volume of film formed and also the tendency of the filter to become clogged.

*Sewage Disposal.*—In a study of the biochemical oxygen demand test as applied to sewage and sludge. Barcroft respirometers have been used in experiments on the effects of various factors on the rates of oxidation of sewage, sewage effluents and activated sludge in contact with the air at 24° C. Under the conditions of test, the rates of oxidation observed were greater than under those of the ordinary B.O.D. test. It also was found that the rate of oxidation of mixtures of sewage and activated sludge was greater than the sum of the rates for the separate constituents, especially during the early stages of oxidation. Maximum rates of oxidation for sewage and sewage effluents were obtained at pH values between 6.6 and 9.0 and for activated sludge at pH values between 6 and 10. These results emphasize the importance of control of pH value in biological processes of sewage treatment.

It has been shown that sewage and sludge previously sterilized by heating, by filtration through a Seitz filter, or by treatment with certain disinfectants, does not absorb oxygen from the air. Inoculation of the sterilized sewage or sludge by the addition of small quantities of untreated sewage or sludge or washed suspensions of certain bacteria (Ps. fluorescens and Ps. pyocyaneus) at once initiates absorption of oxygen.

The addition of KCN to sewage in concentrations of M/200 to M/10,000 reduced the rates of oxidation during the first 5 hours, but afterward the effect of the cyanide gradually decreased until the rate of oxidation became the same as for the sewage alone.

Some experiments have been carried out on the effect of the protozoan flagellate *Polytoma uvella* on the oxidation of sewage and sewage sludge by air. This organism initiated the oxidation of previously sterilized sewage but was not so active in this respect as certain bacteria.

The oxidation of solutions of an ammonium salt, sugars, amino acids,

formate, lactate, glycerol, olive oil and phenol in the presence of activated sewage sludge has been studied. The rate of oxidation of ammonia reached a maximum of pH 8.0 to 9.2. All substances except phenol were oxidized.

Investigation of the nature and amount of colloidal and other dispersed matter in sewage has been continued. During the past year the work has included experiments on the flocculation of dispersed matter by passing streams of air, oxygen, hydrogen and nitrogen through samples of domestic sewage at 25° C. All four gases cause coagulation of a considerable amount of dispersed material in a few hours. Even particles so small as to pass an ultrafilter were coagulated by the action of the gas bubbles.

*River Mersey Investigation.*—Progress has been made in the River Mersey study, begun in April 1933, with the object of determining the effect of discharges of crude sewage into the estuary on the amount and nature of silt and other solid matter deposited.

During the past year hydrographic observations have been made on sections of the estuary, noting rates of movement under various tidal conditions; the banks exposed at low tide have been surveyed, and an attempt has been made to determine the stabilities of different banks. Samples of water have been examined at different depths and states of tide; likewise, numerous samples of solid matter from exposed banks. The nature and quantity of sewage and trade effluents discharged into the estuary have been studied.

The report of the Director of Water Pollution Research gives detailed information, with illustrative tabulations of data, on all of the foregoing topics. The report is a valuable addition to the notable series of reports which have been issued annually by the Board since its organization in 1927.

H. W. Streeter

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## SEPARATE SLUDGE DIGESTION. OPERATION OF PLANT AT BIRMINGHAM (ENGLAND) DRAINAGE BOARD'S YARDLEY WORKS *

By E. F. Steele

The Yardley sewage treatment plant was designed to treat 3 m.g.d. of sewage by primary and secondary sedimentation tanks, bacteria beds and humus tanks with additional facilities for storm water storage.

* Paper presented at Midlands Branch Meeting of the Institute of Sewage Purification held at Birmingham, England, January 26, 1935, and printed in *The Surveyor*, 87, 207–8 (Feb. 1, 1935).

Separate sludge digestion was later provided to prevent odor nuisance in the closely built up area about the works.

Sludge is pumped direct from the sedimentation tanks to the primary digestion tanks, of which there are seven, each 61 ft. long, 31 ft. wide and 14½ ft. working depth. These tank floors drain to a sump from which the sludge may be transferred by gravity or by pumping through the two inlets of each of two secondary digestion tanks having a total capacity of 4,000 cu. yds. The primary tanks are provided with adjustable weirs and valved outlets by means of which depth of filling and decantation of water can be controlled. The excess water is discharged to the secondary tanks. Floating collectors of steel with copper bearings and vacuum valves are placed on each primary tank and are equipped with manholes for ventilating and inspection. Gas is drawn off through a flexible pipe and passes through a reflux valve before reaching the common collecting main. The gas is used for heating the primary sludge by means of circulating water pumped through a heat exchanger and coils in the bottom of the primary tanks.

*Method of Starting up Digestion Tanks.*—About 500 cu. yds. of sludge from the secondary digestion tank, which had been run into trenches and had commenced alkaline digestion, were pumped into a primary digestion tank and raw sludge from the sedimentation tanks added at intervals of 3 or 4 days. Vigorous fermentation began within 30 hours, the gas and air mixture being allowed to escape from the gas collectors, meanwhile, until all the air was displaced. The other tanks were started by seeding with this ripe sludge and adding raw sludge.

*Operating Methods.*—For continuing the digestion process in operation it was found best to charge all seven tanks twice each week, first by removal and second by displacement. During the winter one of the primary tanks was used as an intermediary between primary and secondary treatment, thereby conserving the heat of the warm sludge from the six heated primary tanks. The temperature of this intermediate tank varied between 78° F. and 73° F. The lag in fermentation in the primary tanks has been further reduced by pumping hot alkaline water from the secondary digestion tank into the raw sludge inlet main. Humus sludge, because it slows up digestion, is returned to the sedimentation tanks where it is mixed with the raw, settling sludge. Surplus water from the secondary digestion tanks is returned to the raw sewage inlet. The digested sludge is conducted to ½ acre drainage beds for air drying, the filtrate also being returned to the intake.

*Results.*—In one year of operation 52,000 cu. yds. of raw sludge have been handled, equivalent to 14 per cent of the weekly capacity of the primary digestion tanks. These tanks have been charged on the average of twice weekly, once by the removal of settled sludge equal to

6 per cent of their total capacity and once by displacement of 8 per cent of water. Gas produced amounted to 24,000,000 cu. ft. and the daily volume is a good criterion of digestion progress. Of the total, 60 per cent was used for heating, 30 per cent wasted and 10 per cent converted into power and light. The average temperature of the digesting sludge was 77° F.

*Operating Notes.*—Sluggish digestion in the primary tanks is helped by quiet circulation for about half an hour, drawing water from the outlet and pumping it to the sludge inlet. Circulation from the bottom of the tank was detrimental and retarded fermentation for 48 hours. Decantation of water from the secondary tanks, before sludge is withdrawn, should be done slowly because its return in large quantities is liable to affect the quality of the final effluent. The gas collectors can be balanced by adjusting the plug cock on the gas supply line. Plug cocks are preferred to wheel operated valves for this purpose. Gas mains and flexible gas pipes should be provided with ample water drainage facilities.

J. K. Hoskins

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## EXPERIMENTS ON THE PURIFICATION OF CREAMERY AND PACKING-HOUSE WASTES

By Max Levine

*Amer. Jour. Public Health*, 25, 171 (February, 1935)

### Experiments with Creamery Wastes

The filter used in this experiment consisted of a metal tank 2 feet square and 6 feet deep. It was filled with coarse cinders retained on a ½ inch screen. The tank contained ventilating ports at the bottom and terminated in a water seal. Skim milk solutions were applied at the rate of 800,000 gallons per acre per day for about 14 hours daily. When the air ports were open, a high degree of purification was obtained. When the ports were closed, the filter clogged and it was necessary to wash out the clogging material in order to obtain adequate flow through the filter.

Two filters were used to study the effect of the dosing cycle. One filter was filled with cinders and the other with 1½ inch to 3½ inch rocks. A skim milk solution was applied to the filters at the rate of 600,000 gallons per acre per day. The dosing cycles were varied from 2½ minutes to 22 minutes. The dosing cycle had little influence on the purification effected by the cinders, but with the coarser rocks, a short dosing cycle was distinctly preferable. With the latter, the run-off and the B.O.D. of the effluent fluctuated with the dosing cycle.

### Experiments with Packing-House Wastes

Studies were made on a small scale to determine whether the salt concentration causes poor results when the activated sludge process is used for treating packing-house wastes. It was found that by using the fill and draw method, the activated sludge process could function with a pickle brine containing 20,000 p.p.m. NaCl. It was concluded that the poor efficiency of the activated sludge process is not caused by the presence of NaCl but probably by the fluctuations in the concentration of the wastes.

Settled packing-house waste was applied to a filter 3½ feet square and 10 feet deep at the rate of 7,000,000 gallons per acre per day for 6 months. The filter was filled with 1 to 2½ inch red granite and was aerated constantly at the bottom. The effluent from this filter was settled in a small Imhoff tank and then applied to a cinder filter, 3 feet square and 8 feet deep, at the rate of 3,000,000 gallons per acre per day. The over-all reduction in B.O.D. varied from 94 to 97 per cent and the organic nitrogen from 90 to 95 per cent.

In another series of experiments, the settled waste was applied to a shallow cinder filter, settled in an Imhoff tank, and then passed through a dolomite filter, 3 feet square and 8 feet deep. The cinder filter could be freed of clogging material by back washing with water and agitation with air. Very satisfactory results were obtained by this treatment and a full scale plant was designed employing this type of treatment. The plant consists of a Dorr settling tank; a shallow washable filter, ¼ acre in area; a dolomite filter, ½ acre in area and 8 feet deep; and a modified Dorr clarifier. The primary washable filter contained cinders which were later replaced by ½ to 1 inch dolomite. The plant was designed to handle 750,000 gallons per day. The results obtained during 1933 show that the preliminary sedimentation reduced the B.O.D. 37 per cent, the first filter and settling tank increased the over-all reduction in B.O.D. to 65.8 per cent and the second filter and settling tank raised this figure to 95.2 per cent.

P. D. McNamee

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## TREATMENT AND DISPOSAL OF SEWAGE IN THE NATIONAL PARKS

By H. B. Hommon

*Amer. Jour. Public Health*, 25, 128 (February, 1935)

Since 1922, there have been constructed 52 sewage treatment plants in the western parks. Many unusual conditions are met in the park

areas. For example, the population of some of the areas will vary from 100 to 2500 people; visitors are accomodated in hotels, lodges, housekeeping cabins, and automobile camps; water may be scarce; and at high elevations, the winters are severe. In designing the plants, three points were considered: (1) protection of streams against contamination and in one park reclamation of sewage for industrial purposes, (2) prevention of odor nuisances, and (3) maintaining architectural and landscape values. A representative plant of each type employed is described.

*Activated Sludge, Rapid Sand Filter and Disinfection.*—Owing to the increasing sewage volume, the septic tank and contact filter at the South Rim of the Grand Canyon National Park were unable to produce an effluent suitable for boiler use or the spraying of lawns. In 1926, it was decided to build a new sewage treatment plant. The maximum sewage flow during 1926 was 100,000 gallons per day with laundry wastes comprising 10 per cent of the total volume. The temperature of the raw sewage varied between 72 and 92° F. An activated sludge plant was designed capable of treating 200,000 gallons of sewage per day. The screened sewage passes into a pre-settling tank with a minimum detention period of 30 minutes. Between the pre-settling tank and the aeration tank is a diversion chamber which can be used to by-pass the sewage around the plant. The two aeration tanks are 42 ft. $\times$ 8 ft. $\times$ 10 ft. and are designed for an average aeration period of six hours. Two longitudinal rows of porous plates in the bottom of the tank receive the air from the blowers through 4-in. pipes. The two blowers have a capacity of 225 cu. ft. of free air per minute against 6½ lb. pressure per square inch at an altitude of 6,500 feet. There is a clarifier tank 16 ft. square with an effective depth of 11½ ft. giving a theoretical detention period of 2 hours. Up to the present time, a coagulation tank 16 ft $\times$ 4 ft. $\times$ 10 ft. has been used as a secondary settling tank. Two rapid sand filters each having an area of 77 sq. ft. and composed of 20 inches of graded gravel and 32 inches of sand receive the effluent from the activated sludge plant. Two semi-automatic chlorine machines disinfect the effluent from the sand filters. A tank 25 ft. $\times$ 16 ft. $\times$ 4½ ft. is used to store the wash water from the filters. The final effluent is pumped 1½ miles to a 200,000 gallon elevated tank by 3-stage centrifugal pumps. The outlets of all pipes containing reclaimed sewage are marked to warn against drinking the water. The reclaimed sewage is used in locomotive boilers, boilers for heating purposes, for watering lawns, for flushing toilets, etcetera. The cost of the reclaimed sewage averages about $0.38 per 1000 gallons.

*Activated Sludge and Disinfection.*—In Yosemite Valley it was desired to erect a plant that would produce no odors, would not be noticeable from the highways on the floor or the slopes leading out of the val-

ley and which would produce an effluent which would not contaminate the Merced River. An activated sludge plant was built with a capacity for 1,200,000 gallons of sewage daily. The sludge is digested and dried on glass covered beds. Liquid chlorine is applied to the influent to the second clarifier by two automatic chlorinators.

*Settling Tanks and Disinfection.*—The sewage is treated in settling tanks and disinfected at places where large rivers or lakes, which are not used as sources of domestic water supplies, are available. Enough chlorine is added to the effluent of the settling tank as it is discharged to the bottom of a contact tank, which has a detention period of 15 minutes, to maintain a residual of 0.5 p.p.m.

*Settling Tanks and Spraying Systems.*—This method of sewage disposal is used at areas which are open to visitors only during the warmer seasons, and when there is little rainfall. At Giant Forest, the effluent from the settling tank is siphoned to sprays in a pipe line 800 ft. long. The sprays operate under a head of 50 ft. Areas are selected where the soil is porous and where vegetation is heavy. Adjacent sprays are closed where the sewage begins to flow in channels and the ground is allowed to dry and the soil raked. No odor can be detected 100 ft. from the plant. In the vicinity of streams, the effluent from this type of plant is disinfected.

*Settling Tanks and Subsurface Galleries.*—At Zion National Park it was not advisable to have the plant above ground so this type of treatment is employed. The tank is 2 ft. below ground and the galleries are 5 ft. below the surface. The effluent passes to three subsurface galleries each 100 ft. long and 5 ft. in diameter. There must be a porous subsoil, adequate storage for sludge, a slow settling rate in the settling tank, and sufficient area in the galleries to successfully operate a plant of this type.

*Septic Tanks and Glass Covered Sand Filter.*—At Rocky Mountain National Park the subsoil is impervious, there is limited space, and the winter temperature is as low as —35° F. The roof of the sand filter is made of wood with glass on the side exposed to the sun. The effluent from the septic tank is applied to the sand filter by an automatic siphon. The plant has operated satisfactorily with temperatures below zero.

*Settling Tanks and Open Trenches.*—At several places settling tanks and open trenches in porous soil are used to dispose of the sewage. The trenches are 2 ft. deep and 2 ft. wide at bottom. The surface growths are removed each spring. This type of plant is practicable where the volume of sewage is small. Plants of this type are operated only during the summer season.

*Settling Tanks, Broad Irrigation, Ponds and Disinfection.*—At the Mammoth Hot Springs area in Yellowstone Park the sewage is treated

by a disposal system which includes a settling tank, 3 chlorinators, broad irrigation, and ponds. One chlorinator is used to disinfect the effluent from the settling tank, another the overflow of the ponds, and the third the small volume of sewage produced during the winter when the plant is inaccessible.

P. D. McNamee

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## EXPERIENCES WITH SEWAGE FARMING IN SOUTHWEST UNITED STATES (SYMPOSIUM)

*Amer. Jour. Public Health*, 25, 2, 119–127 (Feb., 1935)

1. Texas, *V. M. Ehlers.*—In some sections of Texas, droughts are intermittent and part of the state is normally arid; hence, land disposal of sewage has been feasible and economical. Of 68 towns in the State using land disposal, 34 grow crops and 2 use sub-surface irrigation. The chief concern has been to dispose of sewage without nuisance and to keep wastes out of dry streams. Crop growing is secondary, though the value of waste water for irrigation has later become apparent.

Some cities purchase land at $25–$125 per acre and operate the farm; others lease the city-owned land to farmers; others donate the water to farmers as they may need it. The best crops include small grains, grasses, cotton and alfalfa. Pecans, walnuts, grape fruit and oranges are profiting by sewage irrigation in some places. Small truck crops irrigated with sewage have included beans, pumpkins, potatoes, peas and asparagus. A few cities dispose of surplus activated sludge in growing roses, tulips and other flowers. The total area being irrigated for crops is about 4,500 acres.

The cost of irrigation to cities ranges from nothing, where the effluent is donated to the farmers, up to $10 per million gallons, assuming no return on the crops. Cities operating their own farms have shown a revenue per acre per year of $25 to $135.

The volume of sewage applied to land varies from 4,500 to 25,000 gallons per acre daily, depending on the character of the soil. Four industrial institutions are disposing of wastes from meat packing, cheese, and milk plants on land at rates varying from 5,000 to 15,000 gallons per acre daily. Where land has not been overdosed, no nuisance has been reported.

As a guide to operators and designing engineers, 11 rules, including the following, are set down: (1) sewage irrigation of vegetables eaten raw should not be permitted; (2) sewage effluents applied to land should have at least 50 per cent of settleable solids removed first; (3) furrow

irrigation is more effective than the border method in preventing pounding and water-logging; (4) water requirements vary with the soil and kind of crop grown; (5) sewage should not be applied to fields in quantities greater than that absorbed within 30 minutes; (6) deep plowing (12 in.) every 6 to 12 months is recommended; (7) reserve acreage should be provided.

2. Arizona, *F. C. Roberts, Jr.*—Data are given on land disposal of sewage at two towns, Tucson (32,506 population) and Casa Grande (1351 population). At Tucson the sewage is screened, settled 30–45 minutes, and then applied to a 1,360 acre sewage farm at a rate varying from 7,500 to 12,500 gallons per acre daily, in winter and summer respectively. The crops grown are barley, corn, alfalfa, maize, sudan grass and cotton. A yield 25–30 per cent greater than that obtained from neighboring land not irrigated by sewage is claimed. The capital cost of the system has been $176,950. The net annual operating cost has ranged from $22,744 down to $3,327, the higher figures representing years in which ambitious programs were carried out. The farm requires five men for its operation and disposes of 2.5 million gallons of sewage daily (average).

At Casa Grande, 25 acres are required to dispose of 150,000 gallons of sewage daily (6,000 gallons per acre). Cotton is the only crop. The yield is usually 2 bales per acre, as compared with 1 bale on the best adjacent farms. The city does not farm the land, but leases it for $30 per year. Chlorine is used to overcome odors due to the staleness of the sewage, at a cost of $183 per year. The net cost to the city is therefore $153 per year (or $2.85 per million gallons of sewage).

3. California, *E. A. Reinke.*—Irrigation of crops with sewage has been practiced in California for many years. Pasadena's sewage farm, the oldest, was purchased in 1887. At present, the sewage from 53 municipalities is being disposed of by irrigation of cultivated crops, from 9 others by irrigation of wild crops, and from another 28 on land with no crops. Thus 90 out of 310 sewered municipalities in California now have land disposal.

In 1933, 46 out of 62 cities reporting, went in for some kind of cropping. Of the 4,050 acres being watered, 3,628 acres were under cultivation, the remainder being wild grass. The cultivated acreage included 340 acres of vegetables (all of varieties to be cooked); 150 acres of dry beans, 63 acres of tomatoes and 1,660 acres of fruit trees and vineyard. The remaining 1,617 acres were planted to alfalfa, fodder crops, sugar beets, hops and cotton.

In 1918 the California State Department of Health adopted regulations concerning the use of sewage effluents for irrigation, which prohibited irrigation of berries and salad vegetables; permitted irrigation

of vegetables harvested in the dry state; and permitted, under restrictions, such uses as (1) for garden truck if not watered 1 month before harvesting, (2) orchards, if windfalls were not gathered for human consumption, (3) melons if raised on hills above the water, and (4) fodder crop if milk cows were excluded from the fields.

Under these regulations, health officials were obviously required to supervise the growers and the regulations proved unsatisfactory. New regulations were adopted in 1933, based on classification of sewage effluents as well as on crops to be irrigated.

The present rules forbid the use of raw sewage and raw or undigested sludge for irrigation of growing crops; make no restrictions on use of well oxidized, highly disinfected effluents, and permit the use of settled and undisinfected effluents on nursery and fodder crops, cotton and sugar beets, but not on vegetables, berries and low-growing fruits.

H. W. STREETER

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## PRACTICAL ASPECTS OF STORING AND HANDLING FERRIC CHLORIDE

BY J. M. POTTER

*Water Works and Sewerage*, **82**, 10 (Jan., 1935)

There are three commercial forms of ferric chloride available:

1. Liquid ferric chloride, an aqueous solution containing 39 to 45 per cent $FeCl_3$ by weight.

2. Crystals, a definite crystal of the formula $FeCl_3 \cdot 6H_2O$ containing 60 per cent $FeCl_3$ by weight.

3. Anhydrous, a water free form containing 98 per cent or more $FeCl_3$ by weight.

Liquid ferric chloride shipments are made in rubber lined tank cars holding 8,000 gallons. The liquor is easily handled and, except for its strongly corrosive nature, offers no storage hazards. Ten thousand gallons should be the minimum storage capacity for plants using tank cars of ferric chloride. Wood, reinformed concrete, or steel tanks lined with rubber and with all exposed exterior surfaces protected with ferric chloride resistant paint are ideal containers.

Crystal ferric chloride is packed in non-returnable, paraffine-lined wooden barrels of 55-gallon capacity, holding approximately 435 pounds. To prevent melting, it is advisable to store barrels in single tiers under dry conditions at temperatures below 98.6° F. The storage space required is approximately 70 square feet per ton of $FeCl_3$.

Anhydrous ferric chloride is shipped in non-returnable steel drums

holding 150 pounds. These drums may be stored in tiers, requiring about 40 cu. ft. of space per ton of $FeCl_3$.

The hygroscopic nature of ferric chloride prohibits the use of dry feeds, and the corrosiveness of solutions prevents the use of ordinary piping and feeding equipment. Rubber, glass, Bakelite, ceramic material or resistant metals such as Durichlor or Hastelloy "C" will resist all concentrations of ferric chloride at normal temperatures.

Solution tanks are necessary for dissolving either crystals or anhydrous ferric chloride. Concentrations of less than 40 per cent are recommended to prevent crystallization and solution strengths should be determined by adding a weighed quantity of ferric chloride to a definite volume of water. Solution tanks of steel, reinforced concrete or wood, rubber-lined and faced with acid proof brick and cement are preferable.

Dilution tanks should be used for preparing and supplying uniform solutions to feeders and may be similar in construction to solution tanks but without the brick facing. Concentrated solutions are diluted to 3 or 4 per cent $FeCl_3$ by adding gauged volumes of water and solution.

A positive displacement or a variable siphon head type of feeder of corrosion-resistant material is recommended for applying ferric chloride solutions. For simple coagulation of sewage, water purification practice for flocculation and sedimentation will give the best results. For sludge conditioning, rapid agitation for 5 or 6 minutes followed by continuous filtration is preferable to the batch method.

R. S. Smith

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## THE PROPOSED CONEY ISLAND SEWAGE TREATMENT WORKS OF NEW YORK CITY

By Richard H. Gould

*Water Works and Sewerage*, 82, 35 (Feb., 1935).

New York City is planning immediate construction of the first part of the Coney Island Sewage Treatment Works in the Borough of Brooklyn. The present flow is estimated at 15 m.g.d. and the ultimate flow at 140 m.g.d. in 1970. The proposed plant will have a capacity of 35 m.g.d.

The sewage that will be immediately tributary to the new plant is now treated in four old, inadequate treatment plants and discharged into Coney Island and Shellbank Creeks with the resulting putrefactive conditions. Sewage treatment in this area is necessary to clean up these creeks and permit the development of the proposed Marine Park as well as to protect the great bathing beaches at Coney Island and Brighton, Manhattan and Rockaway Beaches.

The treatment plant is located on Shellbank Creek where little dilution is available and it is proposed to carry the plant effluent through an 8,300 ft. outfall to an outlet structure bordering the main channel in Rockaway Inlet leading to Jamaica Bay. Here the tidal currents trend toward the open ocean rather than toward the nearby beaches.

Consideration of conditions prevailing at the proposed outlet indicate that during the summer the plant effluent should be free from visible suspended solids and reasonably free from bacterial pollution. During the winter removal of most of the settleable solids is thought the only treatment necessary. These conditions would be met by the activated sludge process or by chemical precipitation and chlorination during the summer and plain sedimentation during the winter. Due to limitations of available site and cost of power, chemical precipitation using lime and iron salts as precipitants has been adopted. Chemicals will be delivered by water in barges. The plant is laid out so that if further treatment is desired in the future, mechanical filters can be added.

Present plans call for digesting the sludge and collecting the gas for use in generating power for plant purposes. The digested sludge will be dewatered on a vacuum filter and will be used for developing topsoil in nearby large park developments, or may be disposed of on land fills or in rubbish incinerators. In the future, as the quantity of sludge increases, it will be more economical to dispose of it by barging to sea. The works are so laid out that sludge may be disposed of by barging to sea either raw or digested, and digested filter cake may be disposed of by trucking or by barging to sea for disposal on land or in refuse incinerators.

R. S. SMITH

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## THE ELIMINATION OF CHECK VALVE SLAM

By H. K. PALMER

*Water Works and Sewerage*, **82** (Feb., 1935)

When a pump suddenly stops, the water in the discharge pipe tends to keep in motion, due to its momentum. If the discharge check can be closed before the water comes to a stop, the water cannot start to flow backwards and the valve will not slam; hence, the valve should be closed rapidly. This can be accomplished by using a valve with extended hinge pin and arm so that the flap can be counterweighted, thus preventing the flap from opening fully but accelerating its return movement. On one test with a four-inch pump discharging into a pneumatic tank under 65 pounds pressure, the slam was eliminated by hanging a weight

on the hinge pin arm that increased the pumping pressure less than one-half pound.

Where it is impossible to make the valve close quickly enough, an air chamber will often provide a cushioning effect and delay stopping the water in the main line. It should consist of a piece of pipe the same diameter as the discharge pipe and about two or three diameters in height so that it will not supply enough water to permit any back flow through the check valve. An air chamber arrangement that has been found very satisfactory has an auxiliary check and a gate valve or plug cock. The auxiliary check should be nearly as large as the main check and is set to admit water to the chamber. The gate valve is adjusted by trial until it limits the flow from the chamber enough to prevent slamming and is then left in that position.

To correct slamming in an existing check valve, an air chamber may be built into the cover of the valve, but the size of the chamber must be carefully adjusted.

R. S. Smith

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## SLUDGE DEWATERING AT THE BALTIMORE SEWAGE WORKS

By C. E. Keefer

*Water Works and Sewerage*, **81**, 403 (December, 1934)

Experiments recently completed at Baltimore indicate that digested sludge can be dewatered by vacuum filtration for about $3.30 per ton of dried solids as compared with an average cost of $6.13 when dried on sludge beds.

One of the first experiments conducted on the mechanical dewatering of sludge was with a German centrifuge. No coagulent was used and the cost was estimated to be about $7.10 per ton of dry solids. The effluent was very turbid, with a 5 day B.O.D. of 9,100 p.p.m. About 35 per cent of the solids passed out of the machine with the effluent.

A more promising investigation was conducted in 1931 and 1932 with two small vacuum filters using ferric chloride and chlorinated copperas as coagulants. The capacity of the filter increased with an increase of coagulant up to a limit. During the winter higher filter capacities were obtained with the use of small amounts of coagulant than during the summer. In the summer it was impossible to obtain a satisfactory cake with less than 7.0 lbs. of ferric chloride per 100 lbs. of dry solids.

Elutriation, or washing, of the sludge was found to reduce mate-

rially the amount of coagulant required for satisfactory filtration at a given rate, the ammonia derivatives and ammonia compounds present diffusing into the wash water to a large extent. By elutriating the sludge with two volumes of water the amino-ammonia nitrogen can be reduced about 55 per cent. When filtering unelutriated sludge with 800 p.p.m. amino-ammonia nitrogen, 7.2 per cent of ferric chloride was required to give a filter rate of 8 lbs. dry solids per sq. ft. per hour. After reducing the amino-ammonia nitrogen content to 95 p.p.m. by elutriation, only 1.3 per cent of ferric chloride was required to give the same filter capacity. The decanted wash water from the elutriation will be less than 0.5 per cent of the sewage flow and the average of several tests showed it to have a 5-day B.O.D. of 158 p.p.m. and 270 p.p.m. of suspended solids.

Estimated costs of filtering digested sludge and other related data are given as follows:

| | Sludge Enelutriated | | Sludge Elutriated | |
|---|---|---|---|---|
| | Using Ferric Chloride | Using Chlorinated Copperas | Using Ferric Chloride | Using Chlorinated Copperas |
| Quantity of anhydrous coagulant per 100 lb. dry solids | 5.25 lb. | 11.00 lb. | 2.50 lb. | 4.10 lb. |
| Filter Rate: Dry Solids per Sq. Ft. per Hour | 6.84 lb. | 7.92 lb. | 7.20 lb. | 7.00 lb. |
| Cost per ton of dry solids | $4.38 | $4.66 | $3.38 | $3.28 |

R. S. SMITH

## KEEPING LIME SOLUTION LINES CLEAN

BY L. H. ENSLOW

*Water Works and Sewerage*, **82**, 57 (Feb., 1935)

To keep pipe lines carrying lime solution free from incrustration, the Richmond, Virginia, filter plant uses a program clock which opens and closes a flushing valve at the inlet of the line every four hours.

If a scale builds up which this scheme of water scouring will not remove, it can be dissolved or loosened by running chlorine water from a chlorinator through the line. The chlorine water reacts with the lime

carbonate to form hypochlorous acid, carbon dioxide and calcium chloride. After the carbonate is all converted, the chlorine solution will attack metallic solution lines. Rubber hose with a joint made by butting ends inside a sleeve of larger diameter hose makes a very satisfactory chemical feed line.

R. S. SMITH

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## DEAMMONIATION OF SEWAGE SLUDGES

BY A. L. GENTER

*Industrial Engineering Chemistry*, 27, 218 (1935)

The resistance of sewage sludges to coagulation is caused by the soluble products of decomposition generated and accumulated in the various sludges. Relatively fresh sludges require much less coagulant than well decomposed sludges. The amino-ammonia nitrogen increases on decomposition and the amount of coagulant is almost directly proportional to it. Sludge containing 100 p.p.m. of amino-ammonia nitrogen required 2.2 per cent ferric chloride while sludge containing 325 p.p.m. required 8 per cent ferric chloride to bring about maximum filtration rates. When the amino-ammonia nitrogen was reduced from 325 to 15 p.p.m., only 1 per cent ferric chloride was needed to effect the same result. This indicates that a large amount of the ferric coagulant is consumed in reacting with the ammonium compounds produced by decomposition and in flocculating the colloids produced by their presence.

Deammoniation, *i.e.*, the partial or total removal of the decomposition products associated in solution with ammonia and its derivatives, can be effected by simple elutriation or by chemical reagents. In practice, it was found advantageous to combine the two procedures. The sludge is treated with formalin, about 2 per cent, and allowed to stand for 17 hours. It is then elutriated with two volumes of water and allowed to settle for 12 hours. The application of heat was found to accelerate the formaldehyde deammoniating-reaction speed. The presence of formalin arrests further ammonification by bacterial activity during the period of treatment. The methane produced by digesting sludge is a potential source of formaldehyde. Excellent results were also obtained by the use of chlorine and hypochlorites.

P. D. MCNAMEE

## BROOKHAVEN REBUILDS ITS SEWAGE TREATMENT PLANT

By W. W. Chalk

*Public Works*, **66**, 13 (February, 1935)

The old sewage treatment plant of Brookhaven, Mississippi, consisting of a twin Imhoff tank and contact filter had become so inadequate that in 1933 several suits were pending against the city. The plant was rebuilt with C.W.A. funds, utilizing as much of the old plant as possible. The plant, consisting of a primary settling tank, separate sludge digestion tank, sludge drying beds, trickling filters, pumping station and chlorinator, was put into service October 1, 1934. Dry-weather flow is 500,000 gallons per day which is increased to a little over 1,000,000 gallons per day during heavy rains. The plant was designed for the larger amount.

R. S. Smith

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## NEW SEWAGE DISPOSAL PLANT AT DECATUR

Anonymous

*Public Works*, **66**, 14 (Feb., 1935)

Decatur, Georgia, with a population of 13,000, put a new sewage treatment plant, serving the southeastern part of the city, into operation on December 1, 1934. Design capacity of the plant is 300,000 gallons per day. Complete treatment is provided, consisting of a bar screen, an Imhoff tank, trickling filter and chlorination. The filter is 90 ft. in diameter and is dosed by a four arm rotary distributor operating under a 24 in. head. Chlorine is fed through a dry feed chlorinator into a chlorinating chamber on the filter effluent line.

R. S. Smith

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## FAIRHOPE SEWAGE TREATMENT PLANT

Anonymous

*Public Works*, **66**, 16 (Feb., 1935)

Fairhope, Alabama, a town of 2,000 population on the eastern shore of Mobile Bay, is building new sewage treatment plant with P.W.A.

funds. The plant will consist of a bar screen, clarifier, sludge pump, separate sludge digestion tank and sand drying bed. A chlorinator will be installed for chlorinating both the influent and effluent of the clarifier. The entire plant, except the bar screen, can be by-passed, permitting the complete shutdown of the plant in winter when there is no bathing in the bay.

R. S. SMITH

## NEEDED: A NATIONAL POLICY ON STREAM POLLUTION

ANONYMOUS

*Public Works*, **66**, 10 (Jan., 1935)

Today small excuse exists for a continuation of our lack of policy regarding stream pollution. Municipalities and industries alike are offenders. Among the reasons tending to perpetuate and intensify present conditions are:

1. Inertia. Any municipality hesitates to discontinue its own pollution of a stream while other serious pollution continues.
2. The cost of waste treatment, which may be a serious hindrance.
3. The fact that present efforts are generally limited by state boundaries.

A national policy on elimination of pollution, fostered and directed by a national law giving a five or ten year program is suggested as a solution. Such a program, carried through in a reasonable way, would create a tremendous amount of employment. Government financing with low interest and construction costs far below those of a few years ago, due to improved methods, should make the burden of sewage treatment a light one in most cases. Losses under a government financing policy should be small.

From the engineering viewpoint, control of design, provision for adequate future operation and the general carrying out of the program would be in the hands of the engineering departments of the state boards of health under the general supervision and coordination of some governmental agency, preferably the Public Health Service.

Many of the problems cannot be solved by the action of one state alone; and the formulation and prosecution of a national policy seem to offer the only prospect of saving our streams from intolerable pollution.

R. S. SMITH

## INDUSTRIAL WASTES INTERFERE WITH IMHOFF TANK OPERATION

ANONYMOUS

*Public Works*, **66**, 12 (Jan., 1935)

An unusual overloading of an Imhoff tank was found in a small Wisconsin city. An Imhoff tank was used for treating the sewage from a population of 1,200. A large creamery was connected to the system and later a three-line pea cannery started discharging 50,000 g.p.d. of wash water, 30,000 g.p.d. of cooling water and the silage juice from the stacked vines from about 800 acres into the city sewers. The Imhoff tank under normal conditions provided 3½ hours detention for the domestic sewage, but the creamery wastes reduced this to about 2¾ hours. When the plant was receiving wastes from both the cannery and the creamery, the detention period was only 28 minutes. Much trouble was experienced with foaming although the gas vent walls were raised 4 feet. Sludge could not be removed in the usual manner, as most of the solids were in the gas vent scum.

In another village an Imhoff tank was handling the sewage from about 135 houses. Wastes from a cheese factory handling about 60,000 pounds of milk daily were discharged into the village sewers after passing through a septic tank. Overloading reduced the removal of suspended solids to a negligible amount. Preliminary biological filtration on a crushed granite filter 7 ft. deep was provided for all wash water from the cheese factory and the whey returned to the farmers for stock feeding. Marked improvement in the Imhoff tank operation resulted.

R. S. SMITH

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*Editor's Note.*—A letter has been received from Dr. Heinrich Blunk, of the Emschergenossenschaft, Essen, Germany, calling attention to the fact that the article by Raymond Gaultier, abstracted in THIS JOURNAL (Sept., 1934, page 1028) was based to a large extent on the work and computations previously reported by Dr. Blunk (THIS JOURNAL, May, 1934, page 613). Dr. Blunk's article referred to the operation of trickling filters and the influence of various factors such as volume of film (schmutzdecke), salt content of influent, temperature, and depth of filter. These data were discussed by Mr. Gaultier without reference to Dr. Blunk's publication.

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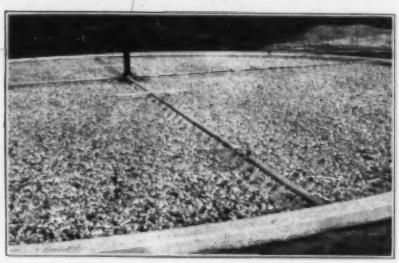

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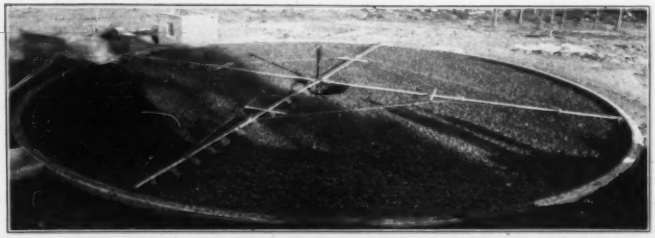

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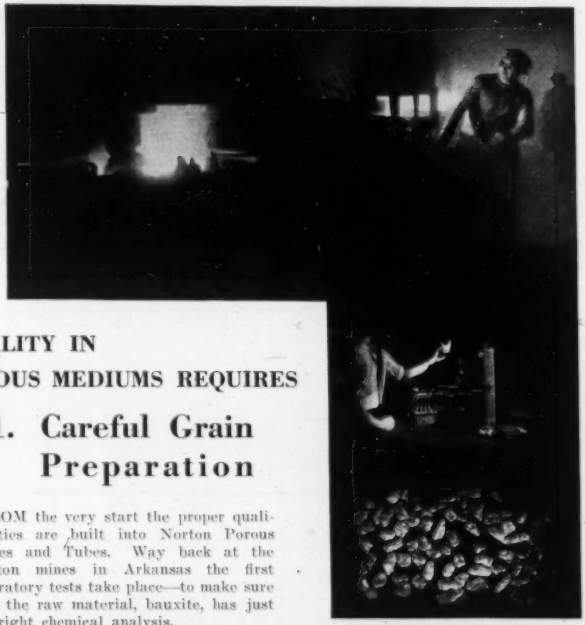

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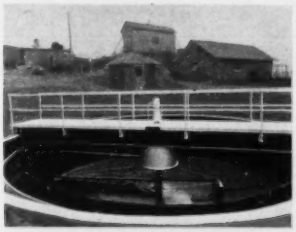

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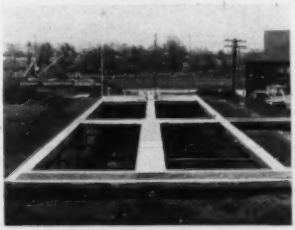

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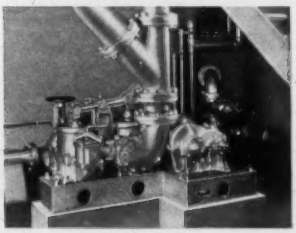

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